Multi-messenger Magnetar Observations (MMOBS)

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PROJECT OVERVIEW

First direct detection of the birth of a (millisecond spinning, highly-magnetised) neutron star, via its multi-messenger signatures.

1. GW signal from a millisecond spinning, highly-distorted NS ($\epsilon \sim Q_{22}/I \gtrsim 10^{-4}$)

2. EM signature triggering the GW search (e.g. shock breakout, supernova)

3. Other EM transients associated to newborn/young magnetars (e.g. Gamma-ray bursts, Fast Radio Bursts) in order to:
   (i) constrain the parameter space of our searches
   (ii) maximizing the extraction of physics information from future detections

Science payback (besides the detection itself):

(a) measuring the birth spin and mass of a newborn NS
(b) setting strong constraints on the EoS of matter at supra-nuclear densities
(c) measuring the magnetic field strength (and interior geometry) of a newborn NS, shedding new light on the origin of NS magnetism and clarifying the link between magnetars and "ordinary" NS

WHY MAGNETARS?

Magnetars and their signature flares

1. Slow-spinning NS (P ~ 2-12 s) with magnetic dipole $B_d > B_{QED} \approx 4.4 \times 10^{13}\ G$ (inferred from spindown rate) and (spindown) age ~ $200 - 10^5$ yr

2. X-ray bright pulsators (either persistent or transient) with $L_X \sim 10^{34} - 10^{36}$ eg $s^{-1} \gg \dot{E}_{rot} = I\omega\dot{\omega} \sim 10^{31} - 10^{34}$ erg s^{-1}

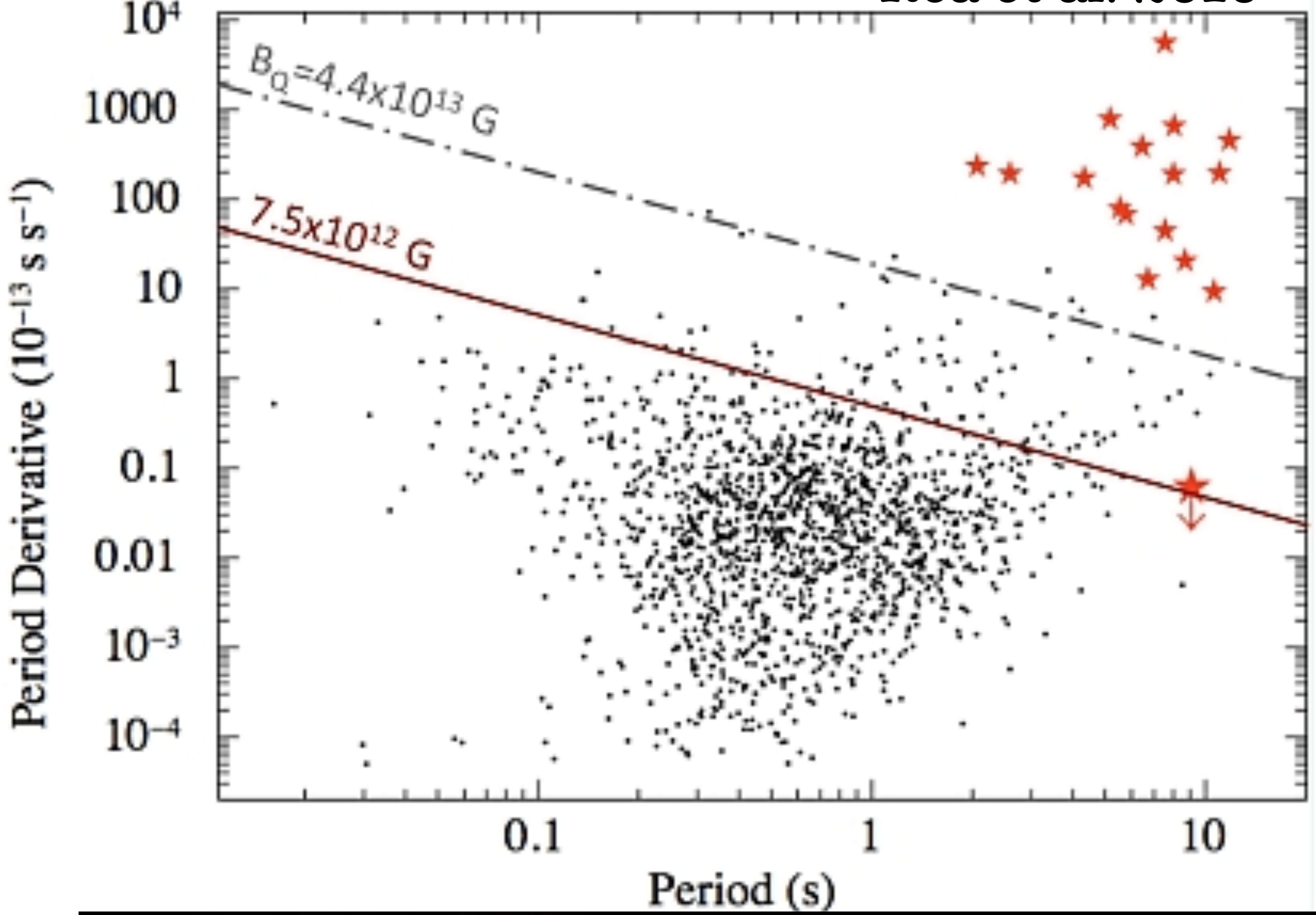
   Magnetic energy is the source of their emission

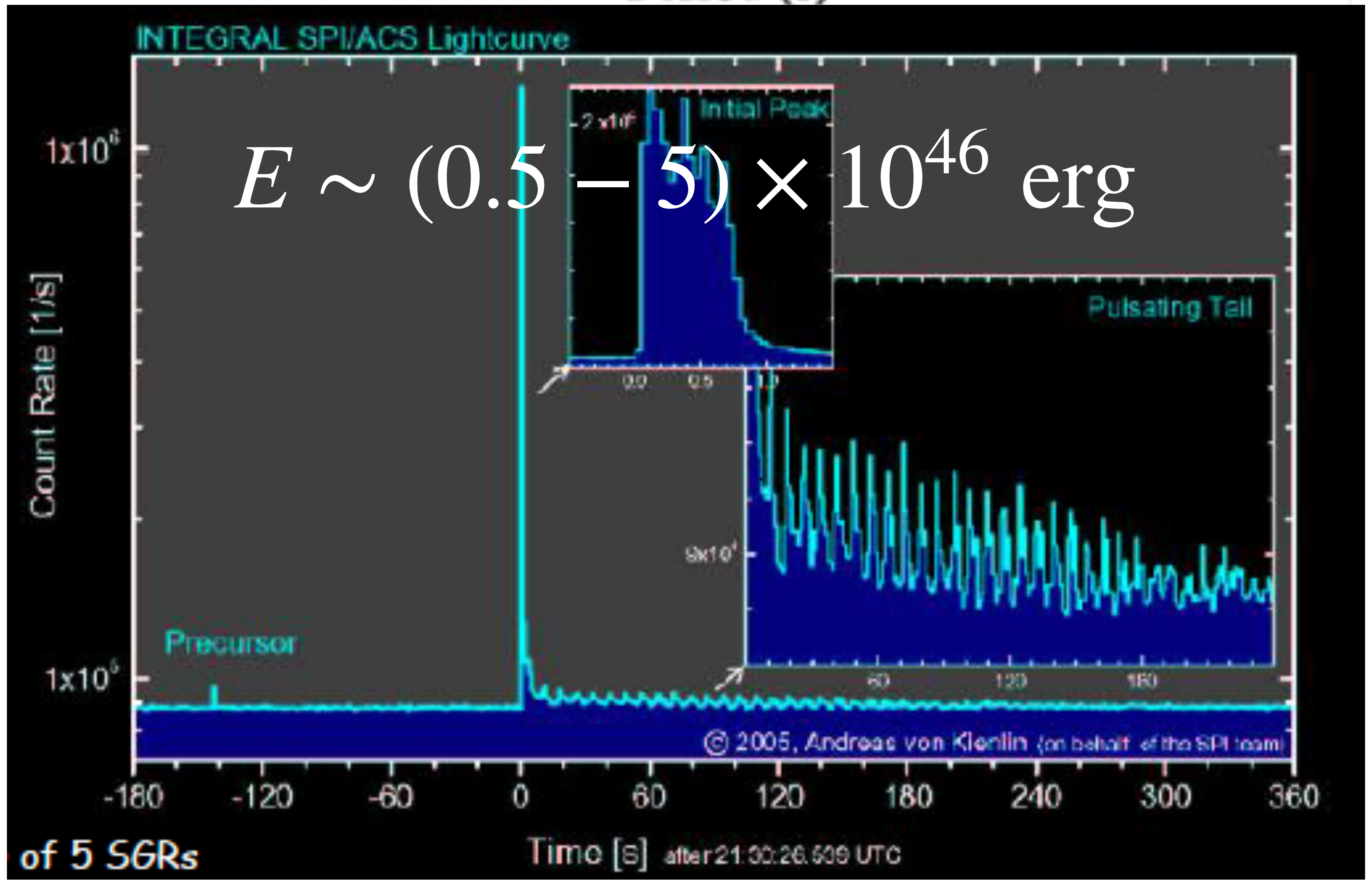
3. Their clustering in P and wide spread in $\dot{P}$ testifies of the decay of the magnetic dipole ($\tau_{dec} \sim 10^{3-4}$ yrs)
   Dall'Osso et al. 2012
   Beniamini et al. 2019

4. Exterior dipole not sufficient. Stronger interior B-field needed
   Thompson & Duncan 1996; Rea et al. 2010; **Dall'Osso et al. 2012**

Strict lower limit $E_{B,int} > 10^{48}$ erg $B_{int} > 2 \times 10^{15}$ G

Rea et al. 2010





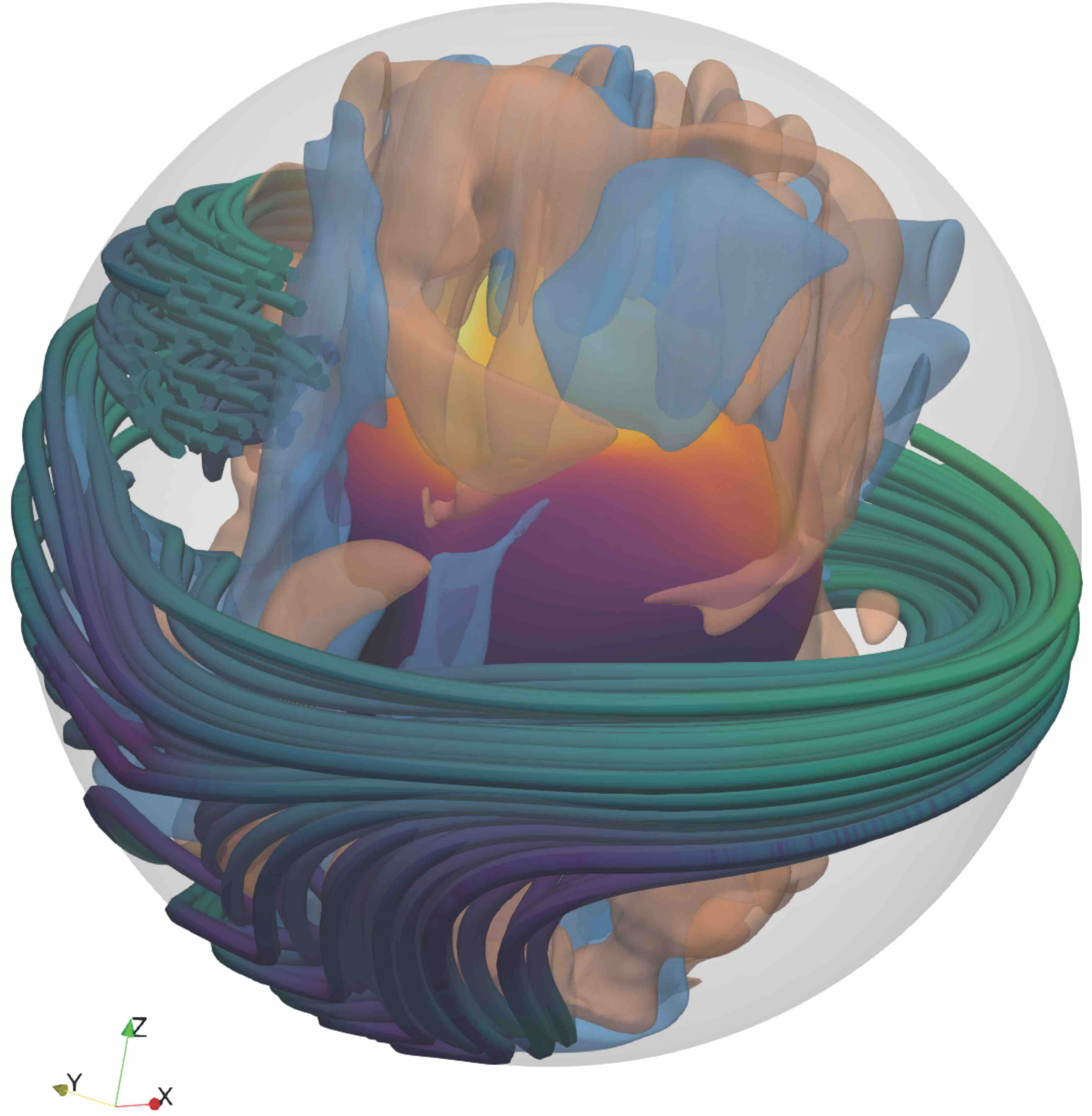
$E \sim (0.5 - 5) \times 10^{46}$ erg

of 5 SGRs

WHAT MAKES THEM SO SPECIAL?

(a) How do magnetars acquire such strong B-fields?

(b) Which factors decide whether a nascent NS will become a magnetar?



Raynaud et al. 2020

(a) A ms-spin at birth was suggested as the key condition for a proto-NS to generate a super-strong B-field through an efficient dynamo.

$$E_{\rm rot} = \frac{1}{2} I\omega^2 \sim 3 \times 10^{52} \text{ erg}$$

$\Rightarrow B_{\rm int} \sim (1-3) \times 10^{16}$ G $\Rightarrow \sim (0.3 - 1) \times 10^{50}$ erg

interior, toroidal B-field

Duncan & Thompson 1992
Thompson & Duncan 1993

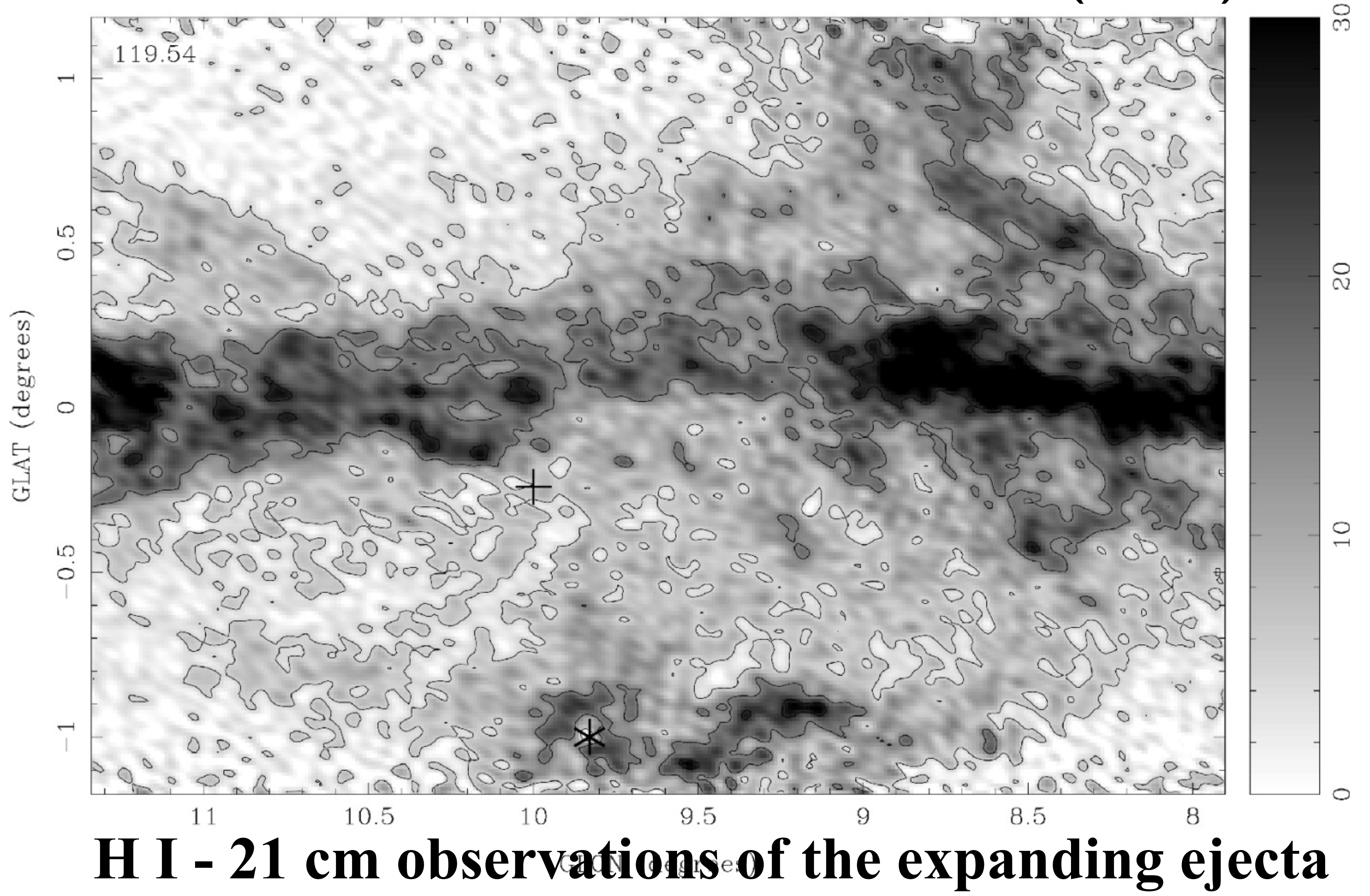
(b) We don't know yet. The mass of the progenitor star is a possibility under scrutiny.

In BNS mergers we may see the effect of fast spin (and strong differential rotation) at work

STELLAR PROGENITORS OF GALACTIC MAGNETARS

SGR 1806-20

Cameron et al. (2005)
McLure et al. (2005)



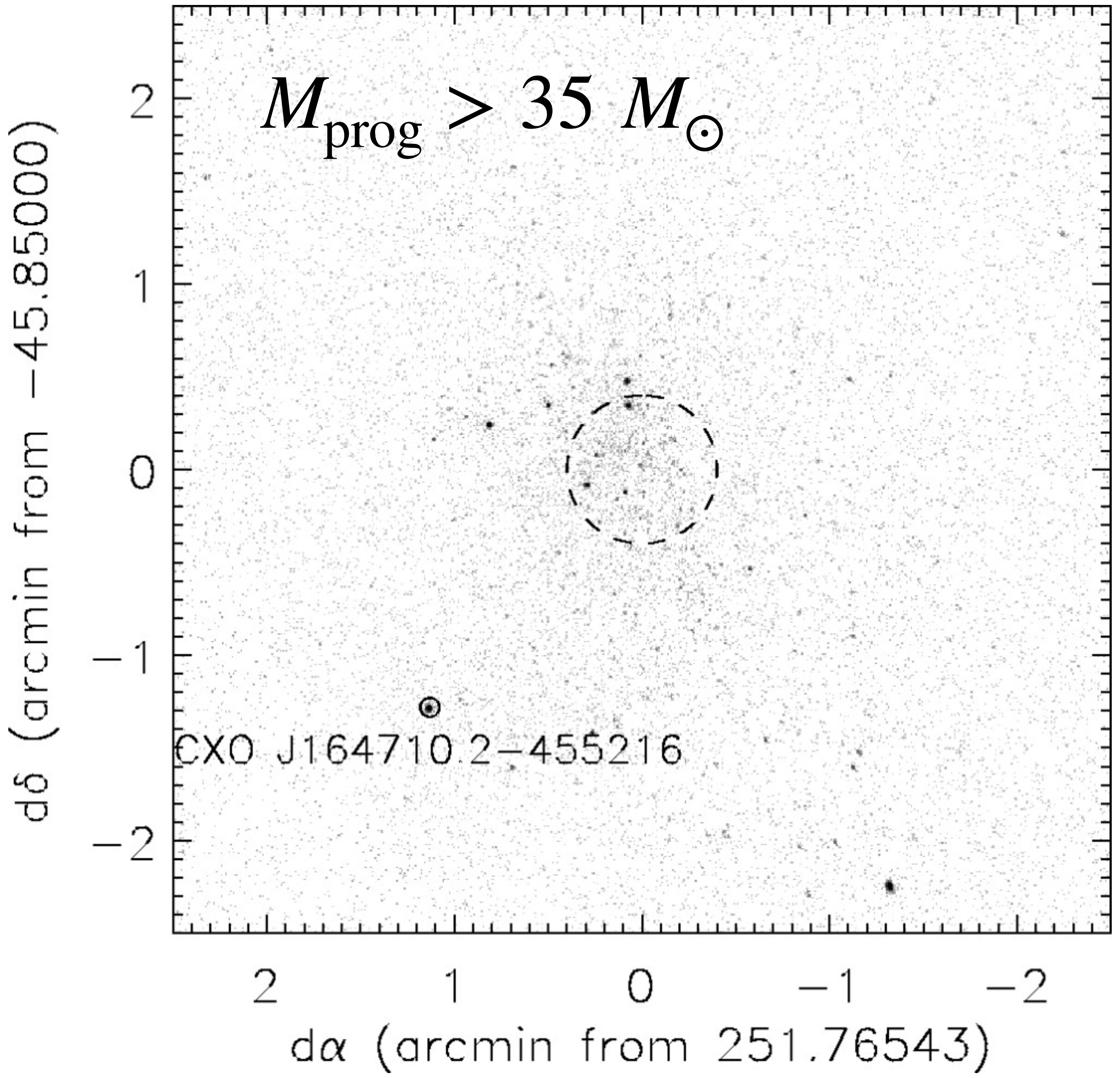
H I - 21 cm observations of the expanding ejecta following the 2004 Giant Flare

DM (mag)	d (kpc)	Star	M_{K_s} (mag)	$M_{\rm Bol}$ (mag)	Log T (K)	Age (Myr)	$M^{\rm OB}_{\rm init}$ ($M_\odot$)	$M^{\rm SGR}_{\rm init}$ ($M_\odot$)
14.0	6.3	#4	−5.1	−8.5	4.46	5	30	35
		#11	−5.2	−8.5	4.44		30	35
14.3	7.2	#4	−5.4	−8.8	4.46	4.6	33	40
		#11	−5.5	−8.8	4.44		33	40
14.7	8.7	#4	−5.8	−9.2	4.46	4	40	48
		#11	−5.9	−9.2	4.44		40	48
15.1	10.5	#4	−6.2	−9.6	4.46	3.4	49	69
		#11	−6.2	−9.6	4.44		49	69
15.4	12	#4	−6.5	−9.9	4.46	3	55	100
		#11	−6.6	−9.9	4.44		55	100
15.9	15	#4	−7.0	−10.4	4.46	2.8	80	120
		#11	−7.1	−10.4	4.44		80	120

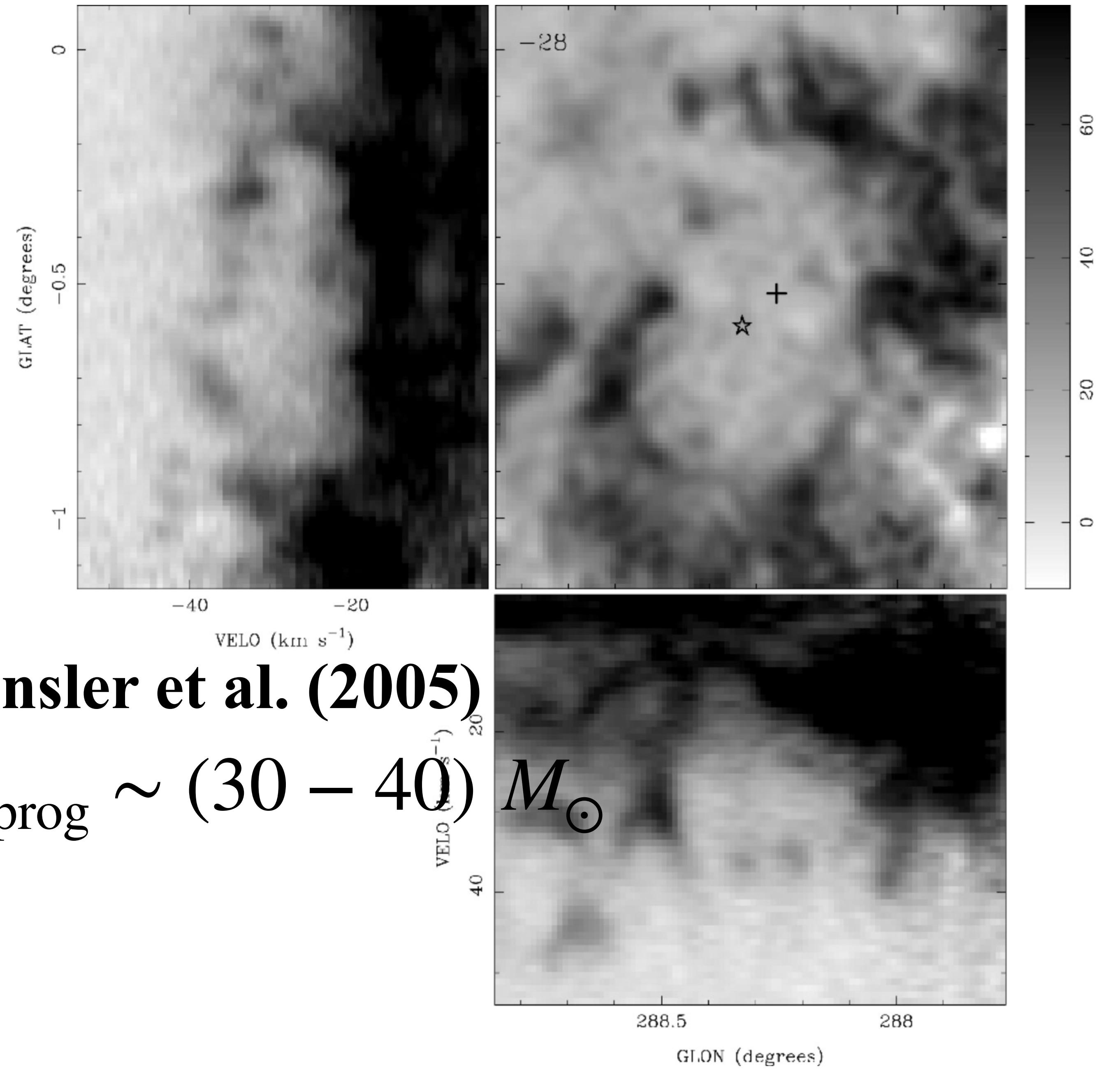
Bibby et al. (2009)

CXO J164710.2-455216

Muno et al. (2006)



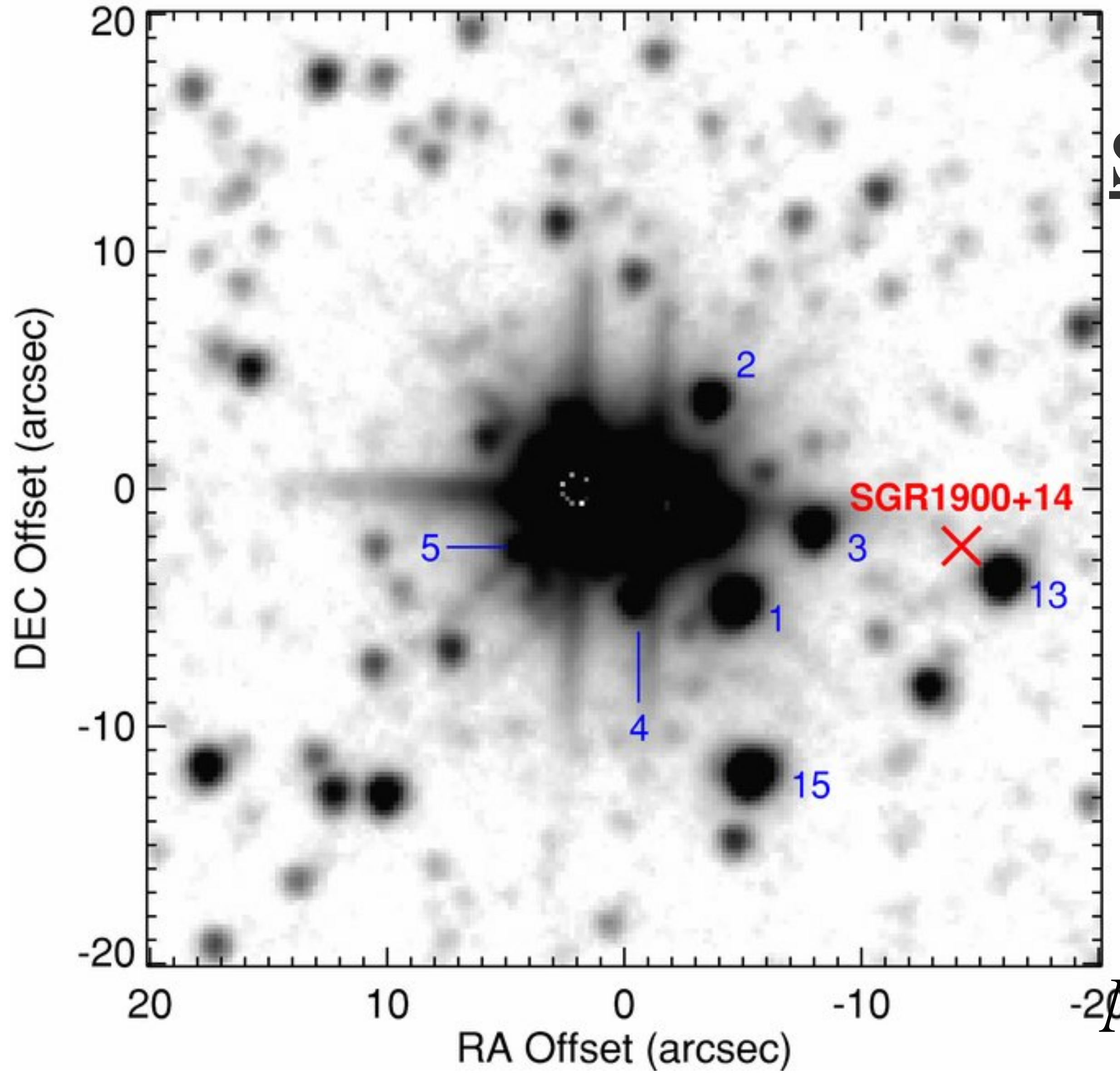
AXP - 1E 1048.1−5937

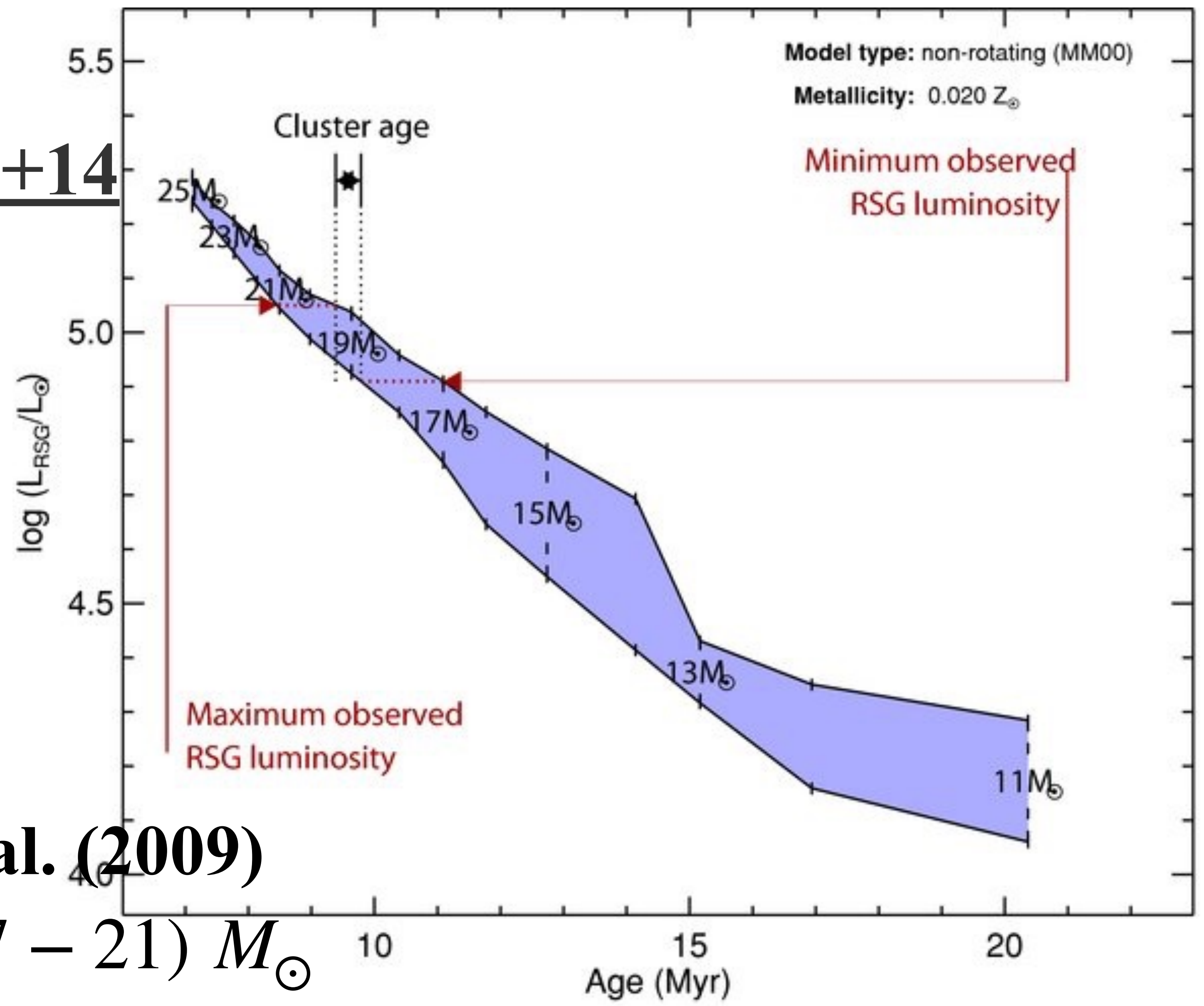


Gaensler et al. (2005)

$M_{\rm prog} \sim (30 - 40)\ M_\odot$

SGR 1900+14



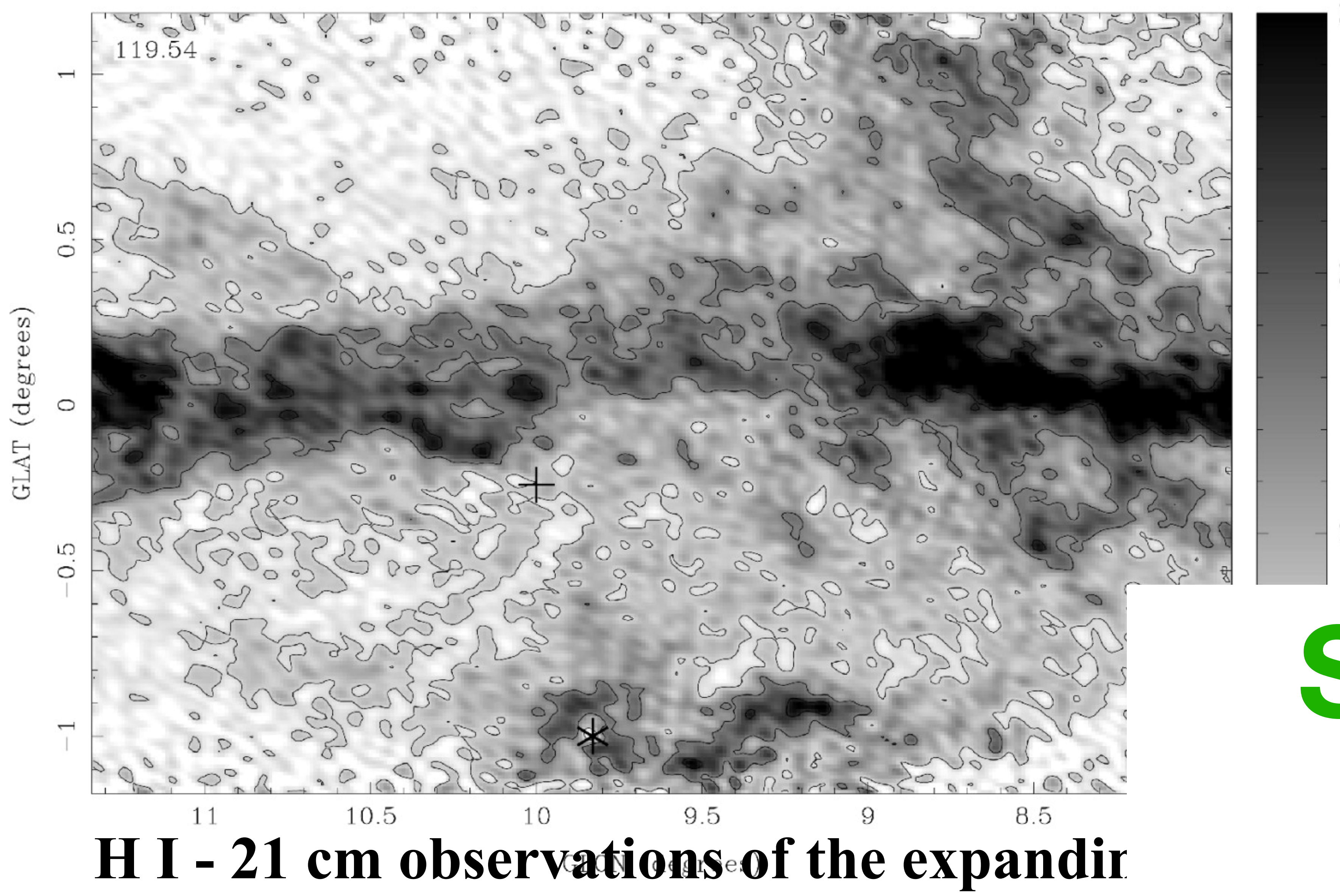


Davies et al. (2009)

$M_{\rm prog} \sim (17 - 21)\ M_\odot$

STELLAR PROGENITORS OF GALACTIC MAGNETARS

SGR 1806-20 Cameron et al. (2005) McLure et al. (2005)



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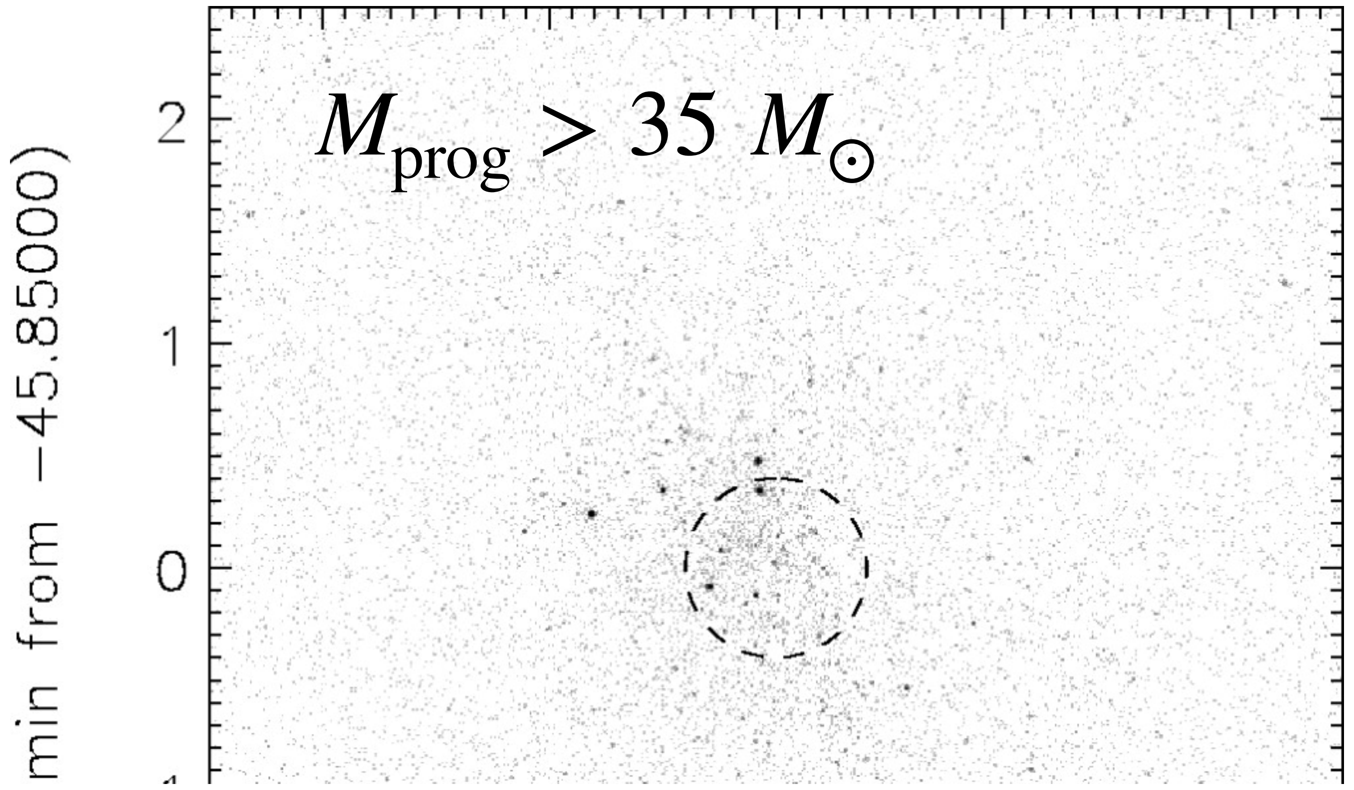
CXO J164710.2-455216 Muno et al. (2006)



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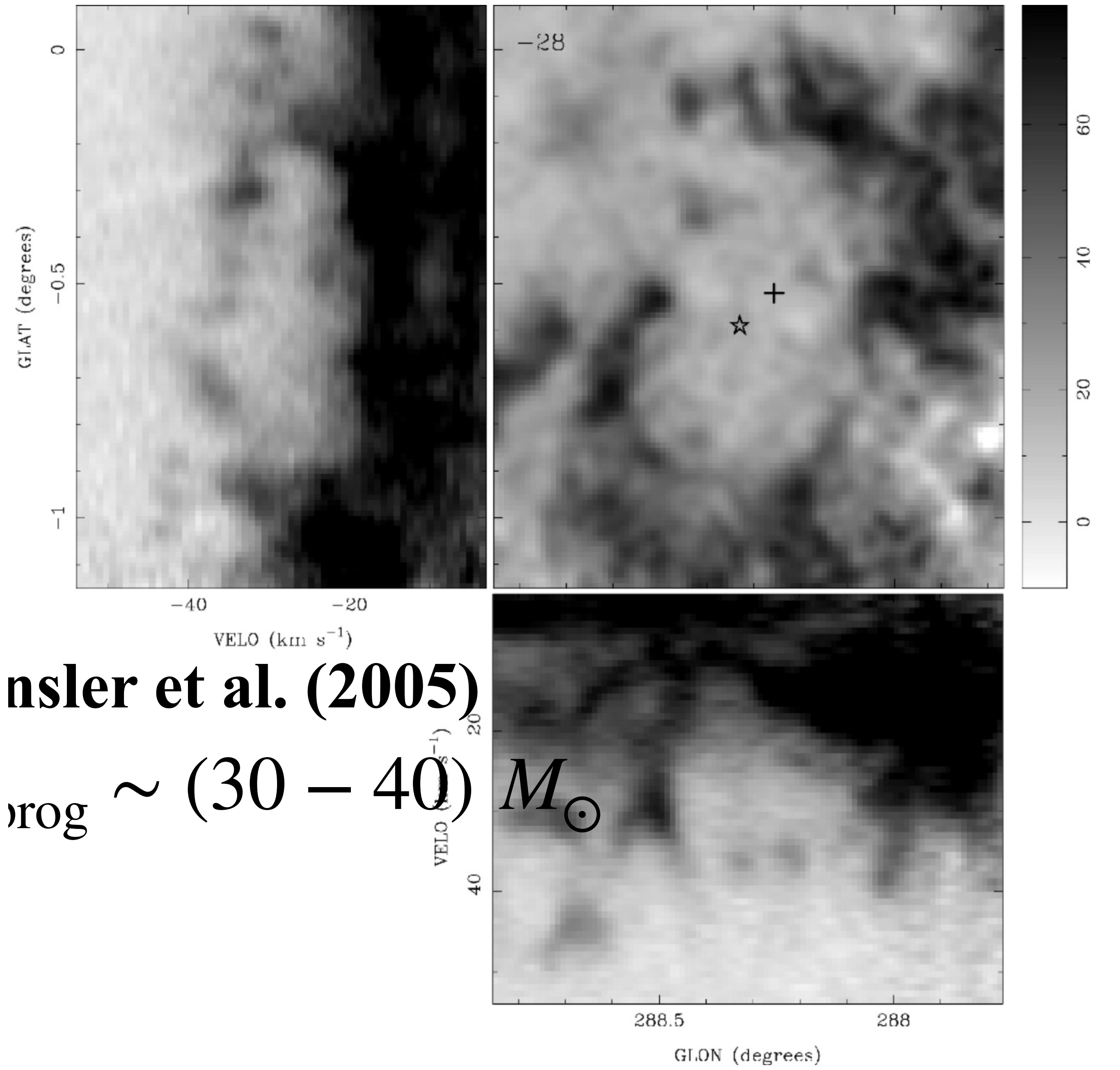

nsler et al. (2005)

$_{\rm rog} \sim (30 - 40)\ M_\odot$

SIMILAR TO STELLAR PROGENITORS OF GAMMA-RAY BURSTS

DM (mag)	d (kpc)	Star	M_{K_s} (mag)	$M_{\rm Bol}$ (mag)	Log T (K)	Age (Myr)	$M_{\rm init}$ ($M_\odot$)	$M_{\rm init}$ ($M_\odot$)
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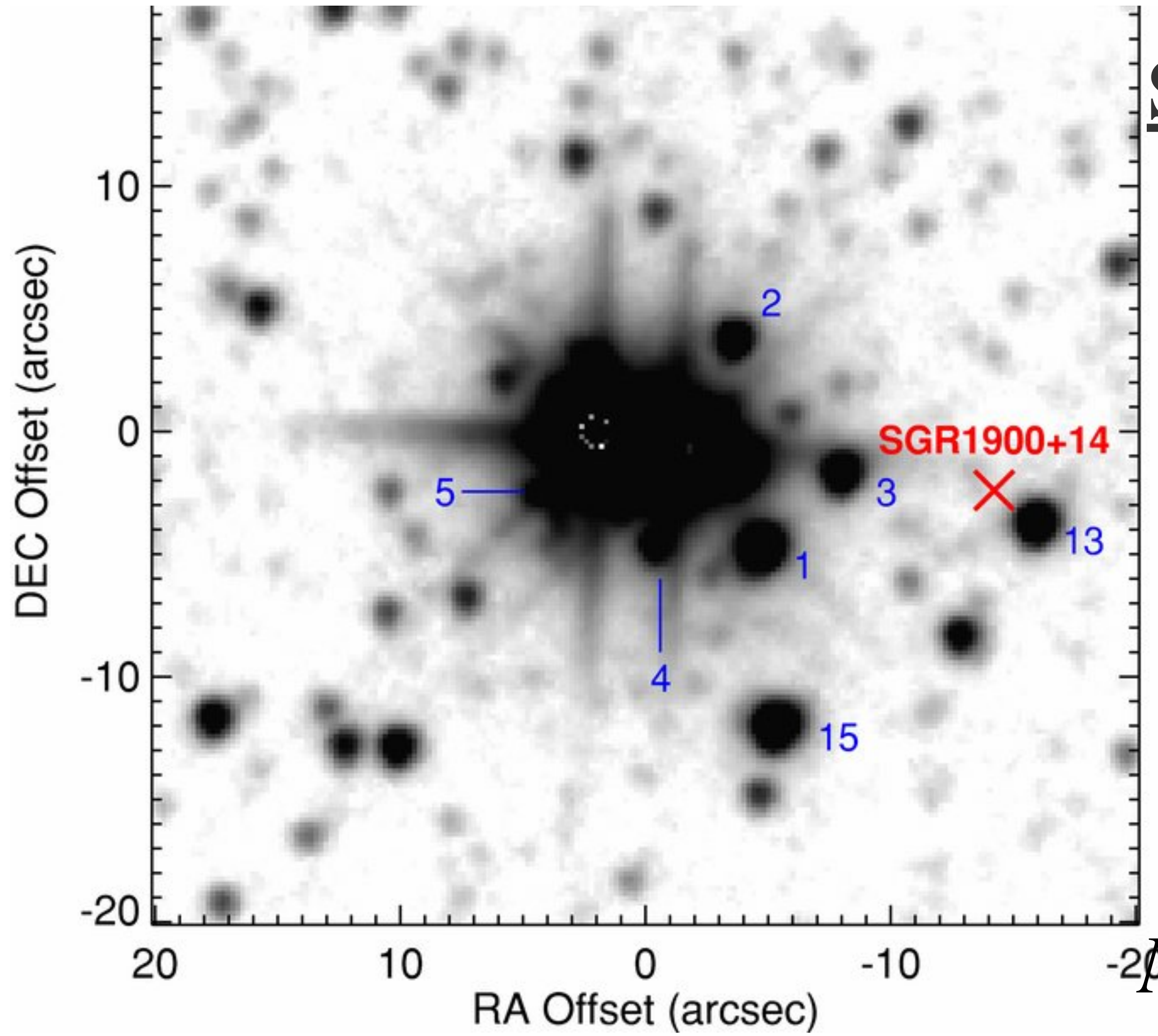
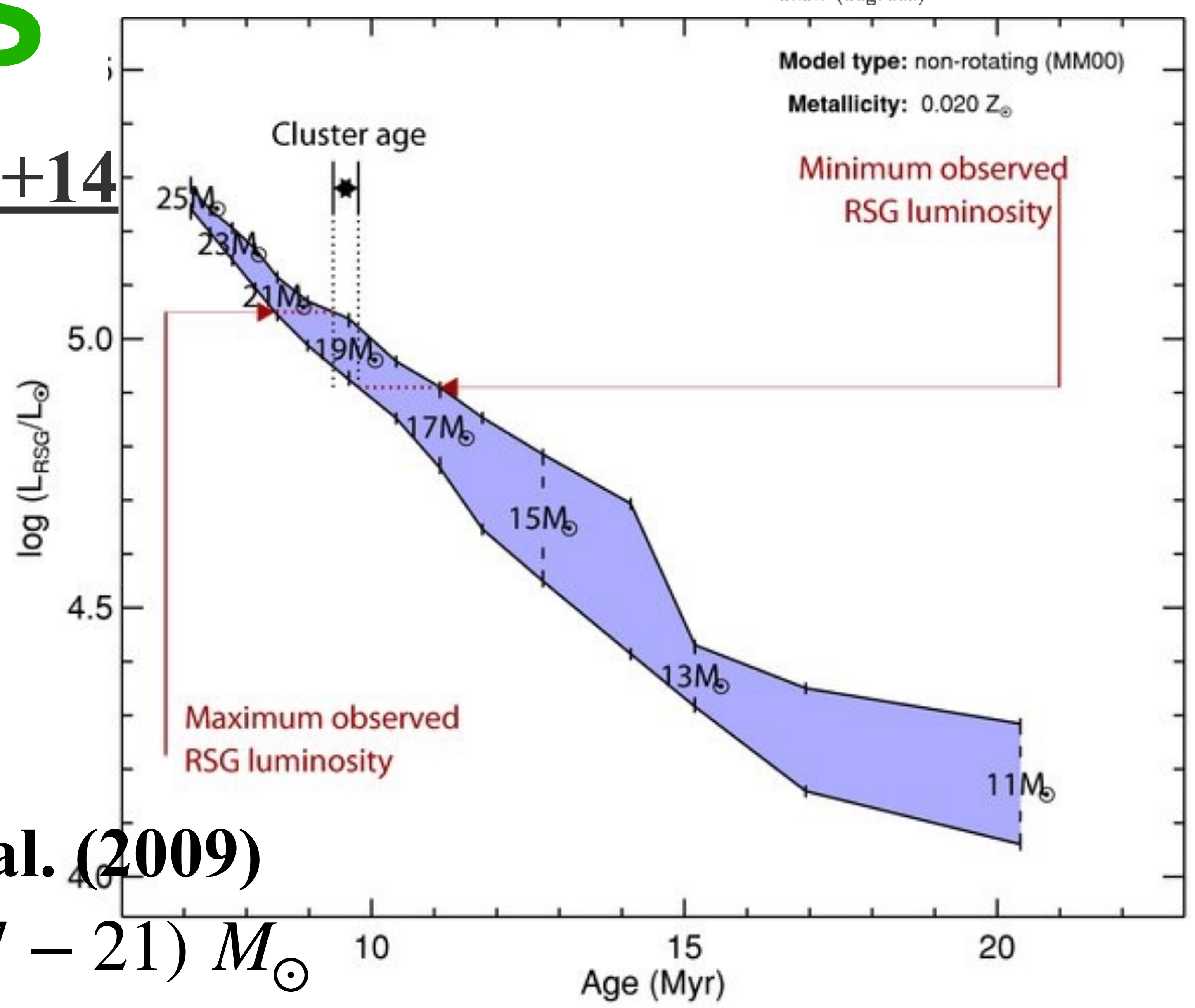
Bibby et al. (2009)



SGR 1900+14

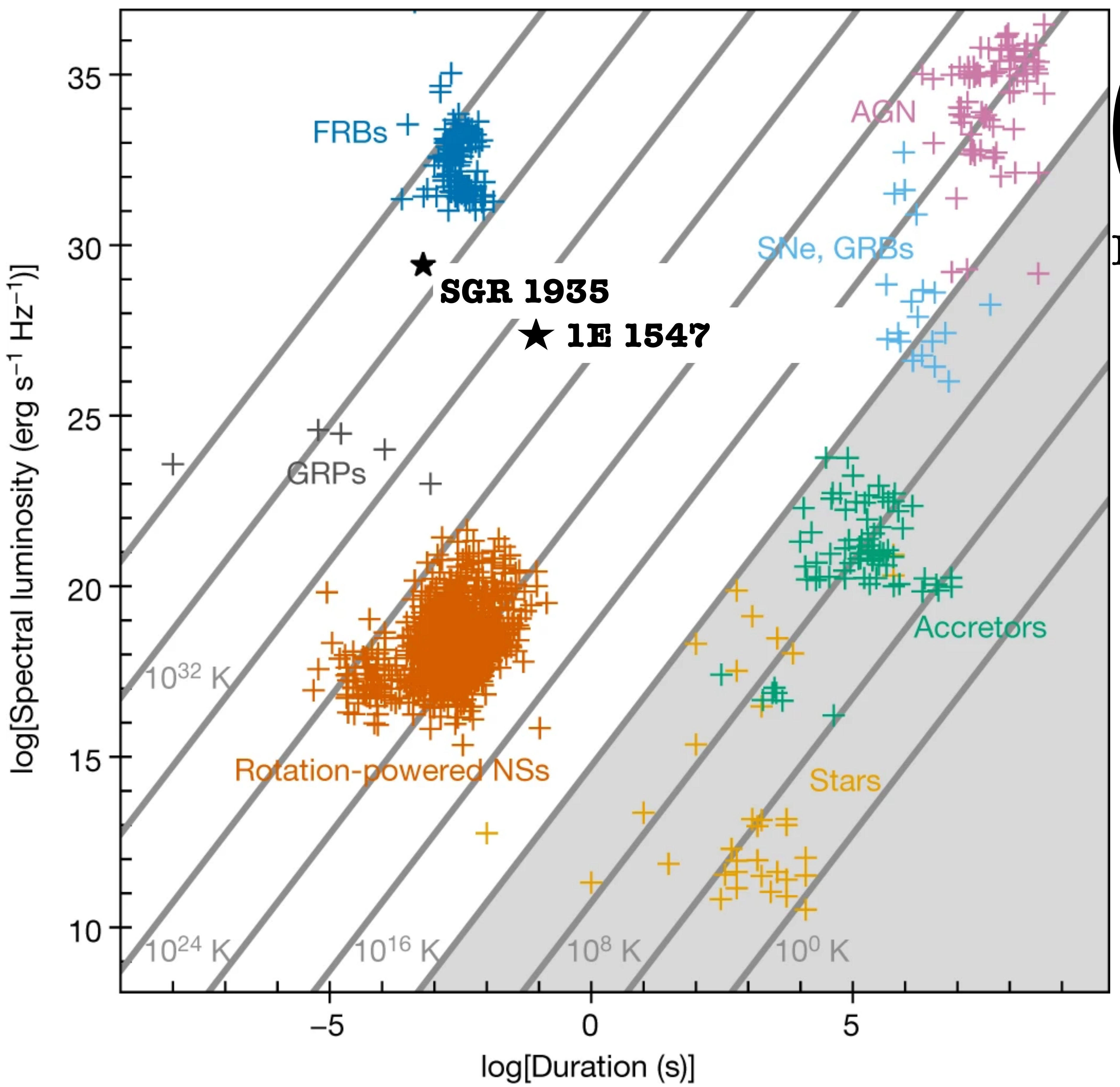


Davies et al. (2009)

$M_{\rm prog} \sim (17 - 21)\ M_\odot$

YOUNG MAGNETAR FLARES AND FRBs

FRB-like emission from young magnetars ($\tau_{age} \sim 10^3$ yrs)



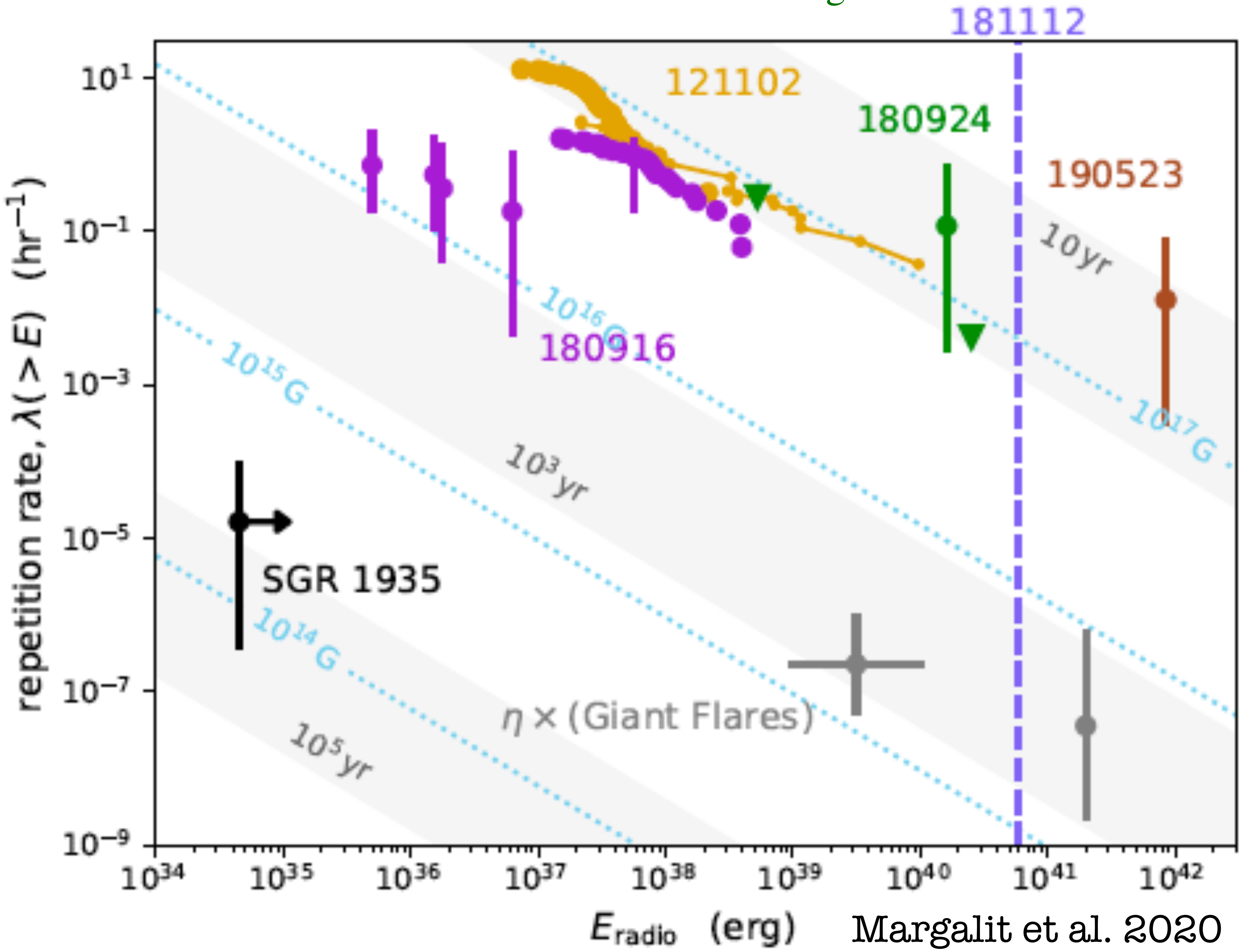
$$\left(\frac{E_X}{E_{radio}} \sim 10^{5\div9}\right)$$

Bochanek et al. 2020
Israel et al. 2020

ms-long radio bursts with $T_b > 10^{31}$ K $\Rightarrow$ coherent emission

$$\Delta E \sim 10^{37} - 10^{42} \text{ erg}$$

Magnetar-like repeating FRBs ($\tau_{age} \sim 30 - 100$ yrs)

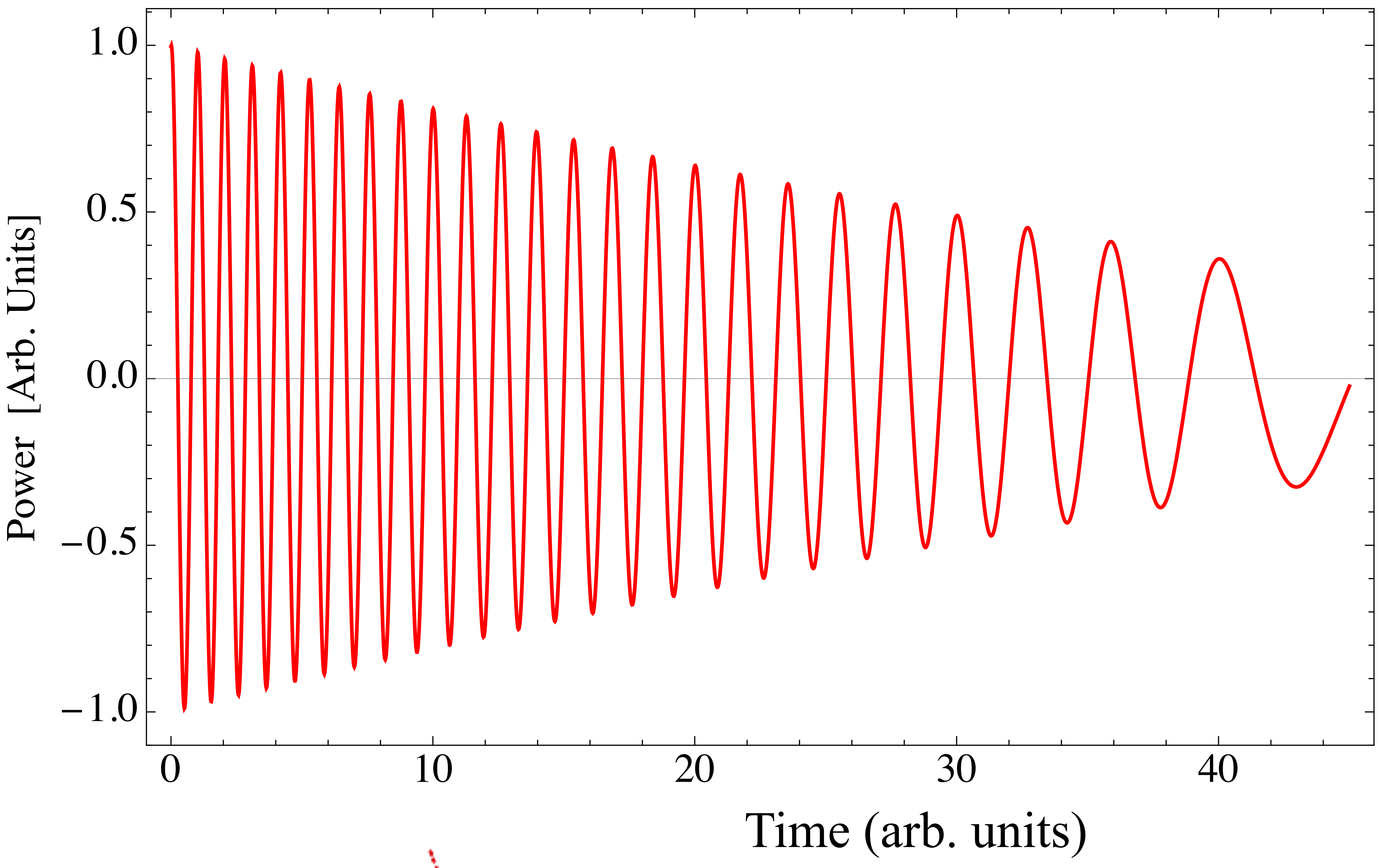


Margalit et al. 2020

$$\langle L_{FRB} \rangle \sim 10^{35} \frac{f_b}{\epsilon_r} \text{ erg s}^{-1}$$

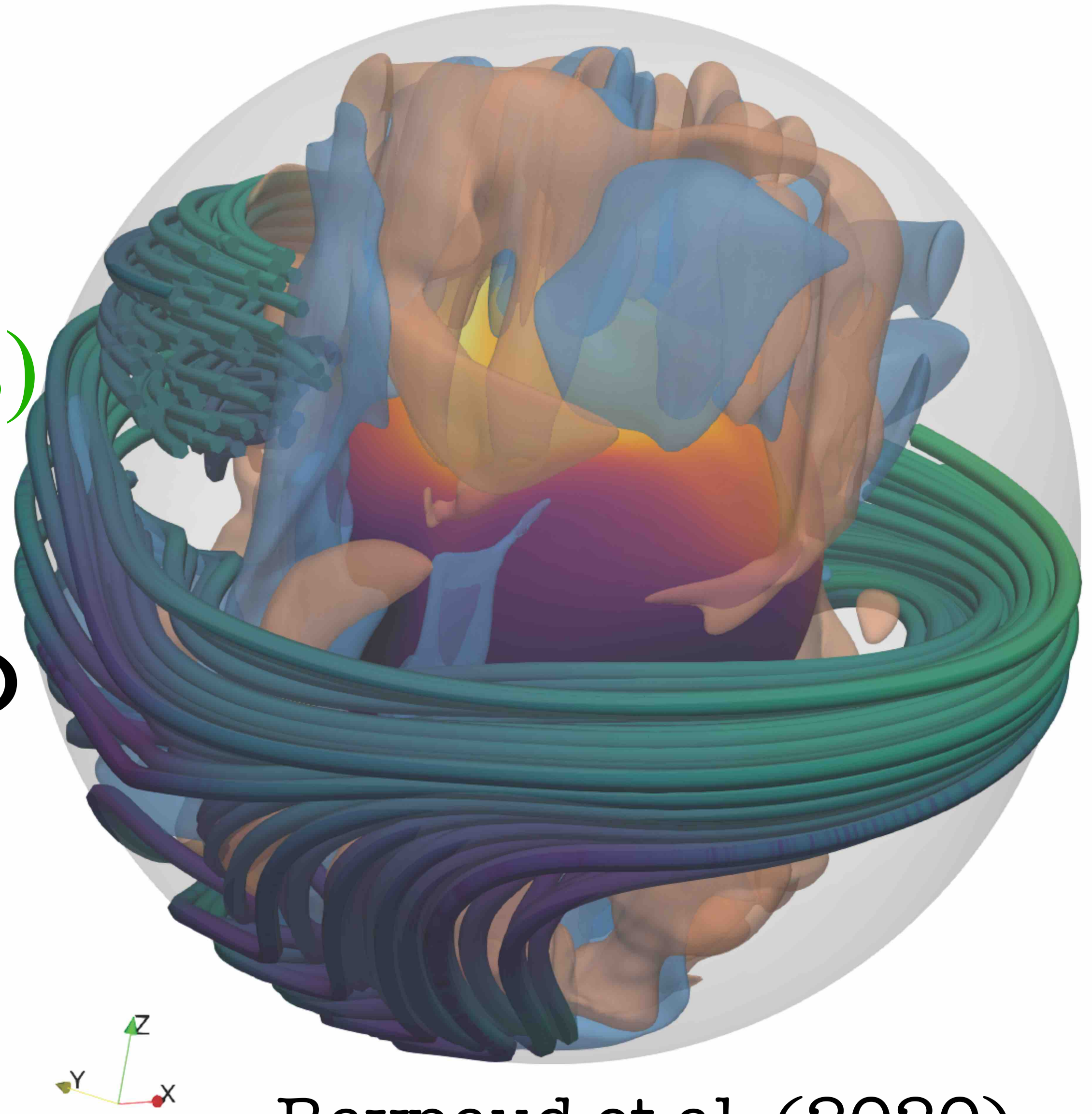
Lu & Kumar 2018
Li et al. 2021

THE MISSING PIECE: GW SIGNALS FROM NEWBORN MAGNETARS



Magnetically-induced large ellipcicity
(ms-spinning magnetars)
$\epsilon \sim 10^{-4} - 10^{-3}$

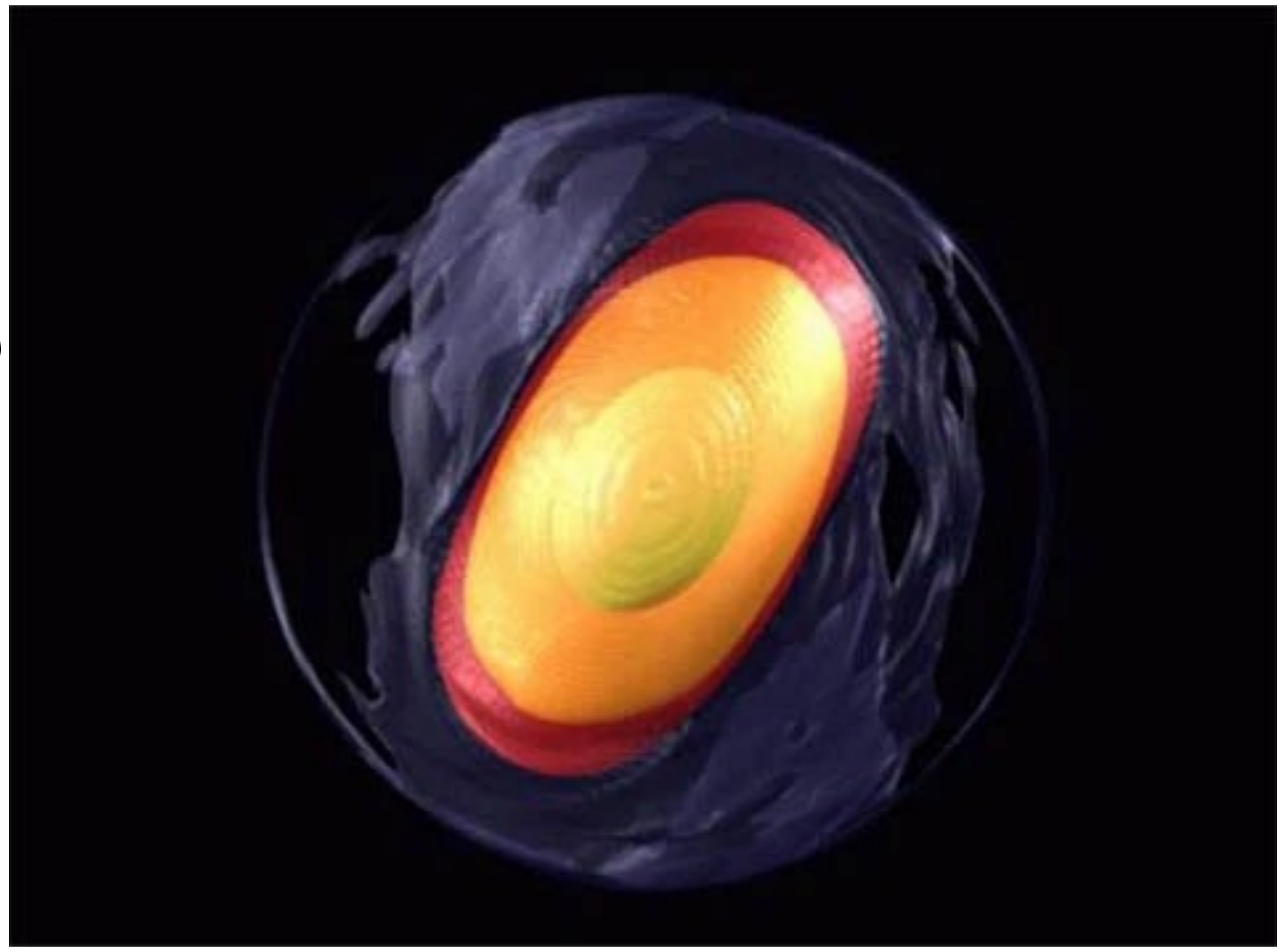
Cutler (2002)
Dall'Osso et al. (2009, 2015, 2018)
Lander & Jones (2020)
Dall'Osso & Stella (2022)

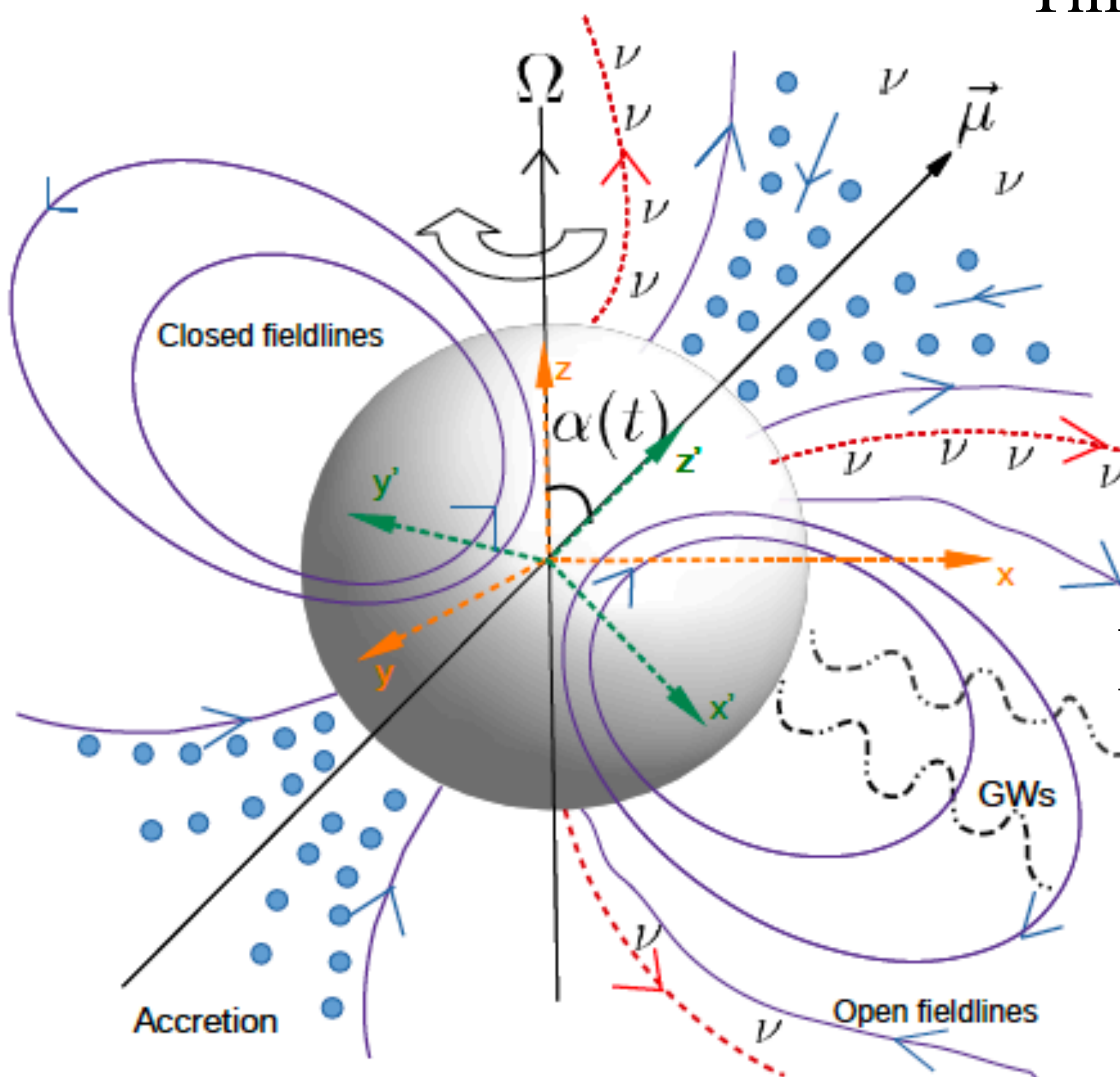


Raynaud et al. (2020)

Secular bar-mode instability
(ms-spinning NS)
$\epsilon \sim 10^{-2} - 10^{-1}$

Lai & Shapiro (1995)
Corsi & Meszaros (2009)





$\epsilon \sim 10^{-6} - 10^{-5}$

Large "mountains" from fallback accretion
(ms-spinning magnetar)

Sur & Haskell (2021)

THE MISSING PIECE: GW SIGNALS FROM NEWBORN MAGNETARS

Top priority @this stage: observation and data analysis efforts, in order to be able to reveal both the GW and EM transients associated to a newborn magnetar.

CCSNe? BNS mergers?

CCSNe: $\sim 7 \times 10^4 \ \mathrm{Gpc^{-3} yr^{-1}}$

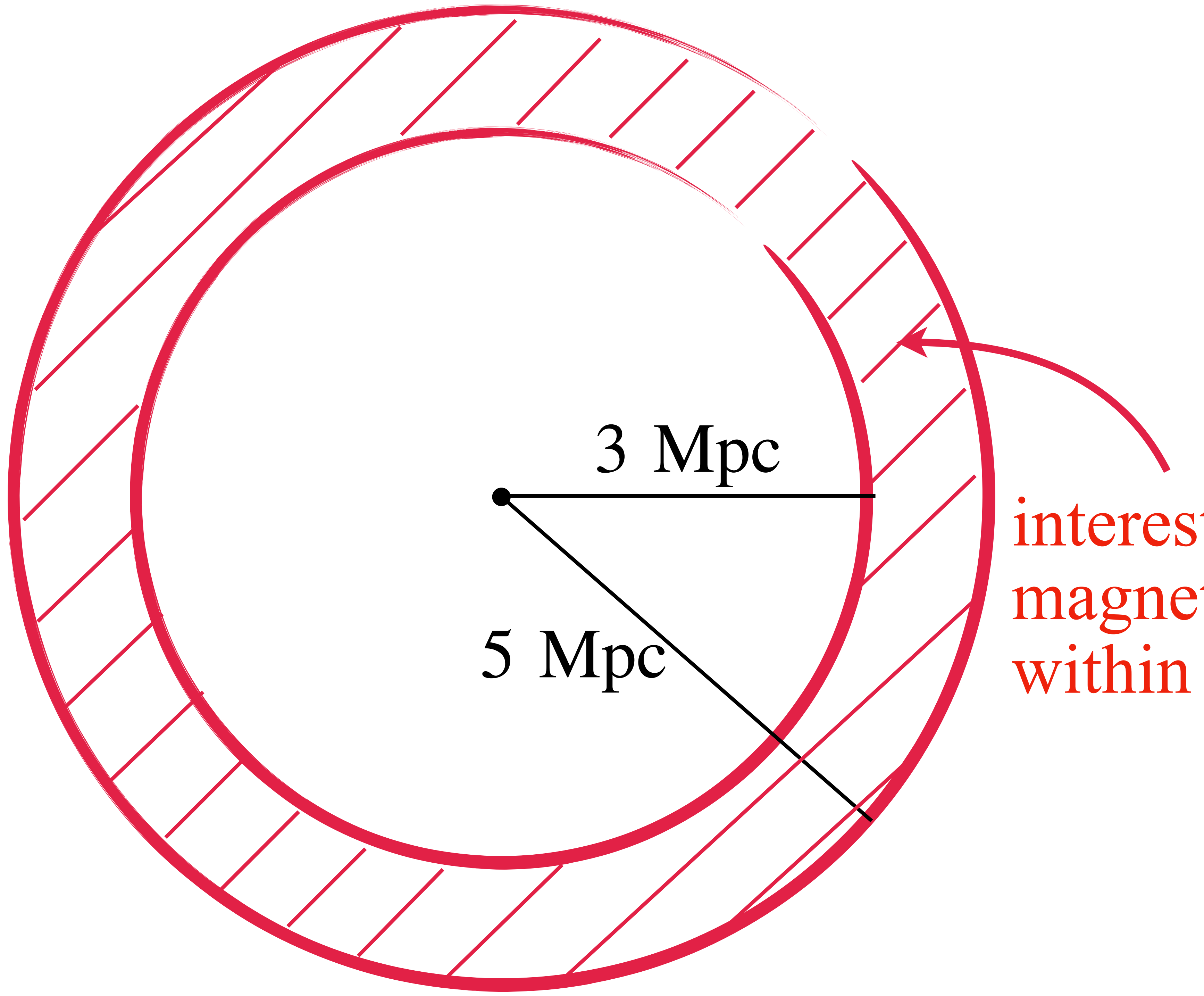
$\lesssim 1 \ \mathrm{yr^{-1}}$

BNS mergers: $\lesssim 300 \ \mathrm{Gpc^{-3} yr^{-1}}$ (LVK O3)

$\lesssim 10^{-3} \ \mathrm{yr^{-1}}$ $\Leftarrow$ within 5 Mpc

$$\mathscr{R}_M \sim 0.1 \ f_{M,-1} \ \mathrm{yr^{-1}} \text{ within 5 Mpc}$$

Larger than BNS merger rate
@D < 40 Mpc, i.e. GW170817



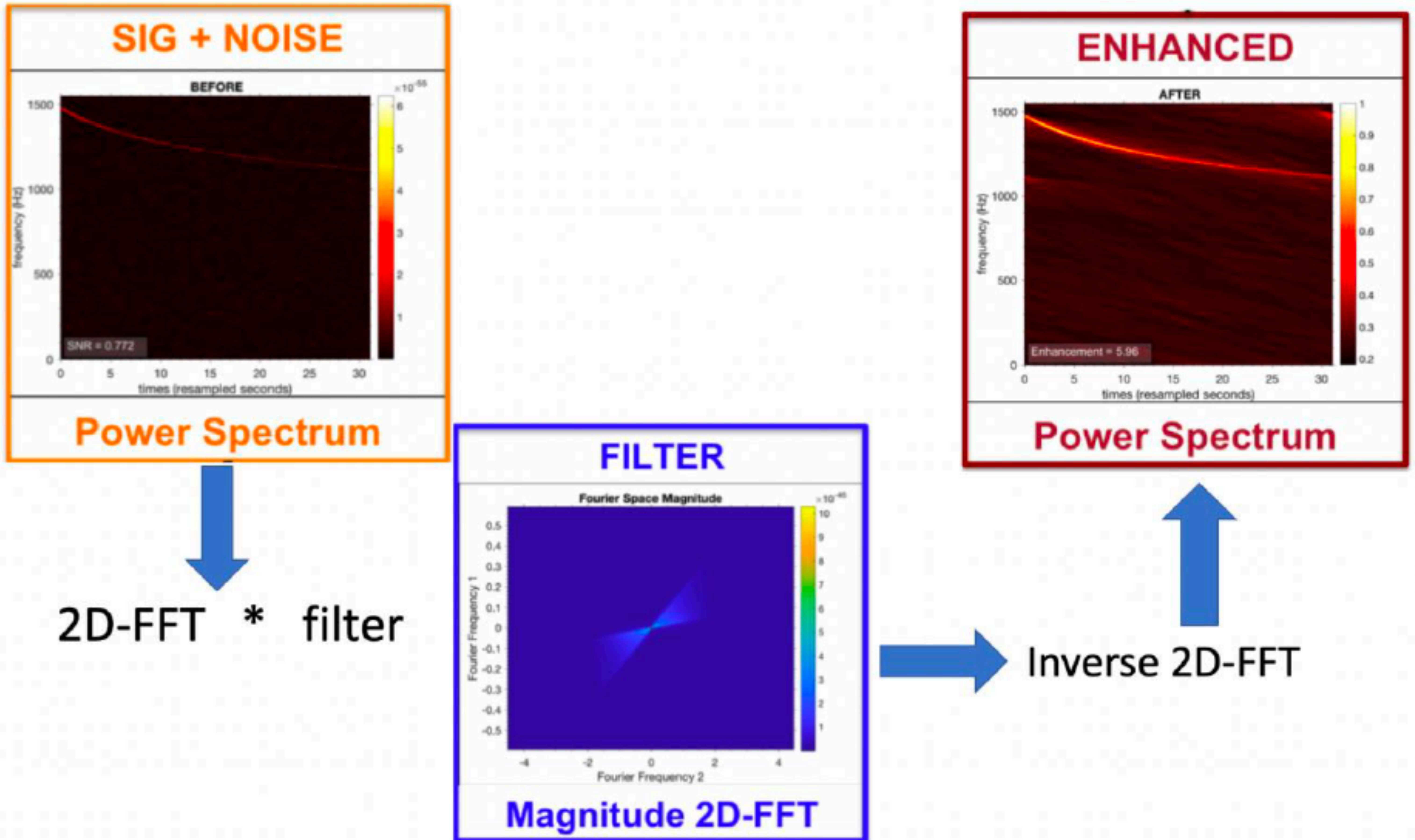
KEY GOAL: ad-hoc search strategies with sensitivity up to 3-5 Mpc

THE MISSING PIECE: GW SIGNALS FROM NEWBORN MAGNETARS

Top priority @this stage: observation and data analysis efforts, in order to be able to reveal both the GW and EM transients associated to a newborn magnetar.

In order to reach our target horizon it will be crucial to:

1. improve existing pipelines or develop novel search methods, by means of template signal injections to check the efficiency of different schemes



THE MISSING PIECE: GW SIGNALS FROM NEWBORN MAGNETARS

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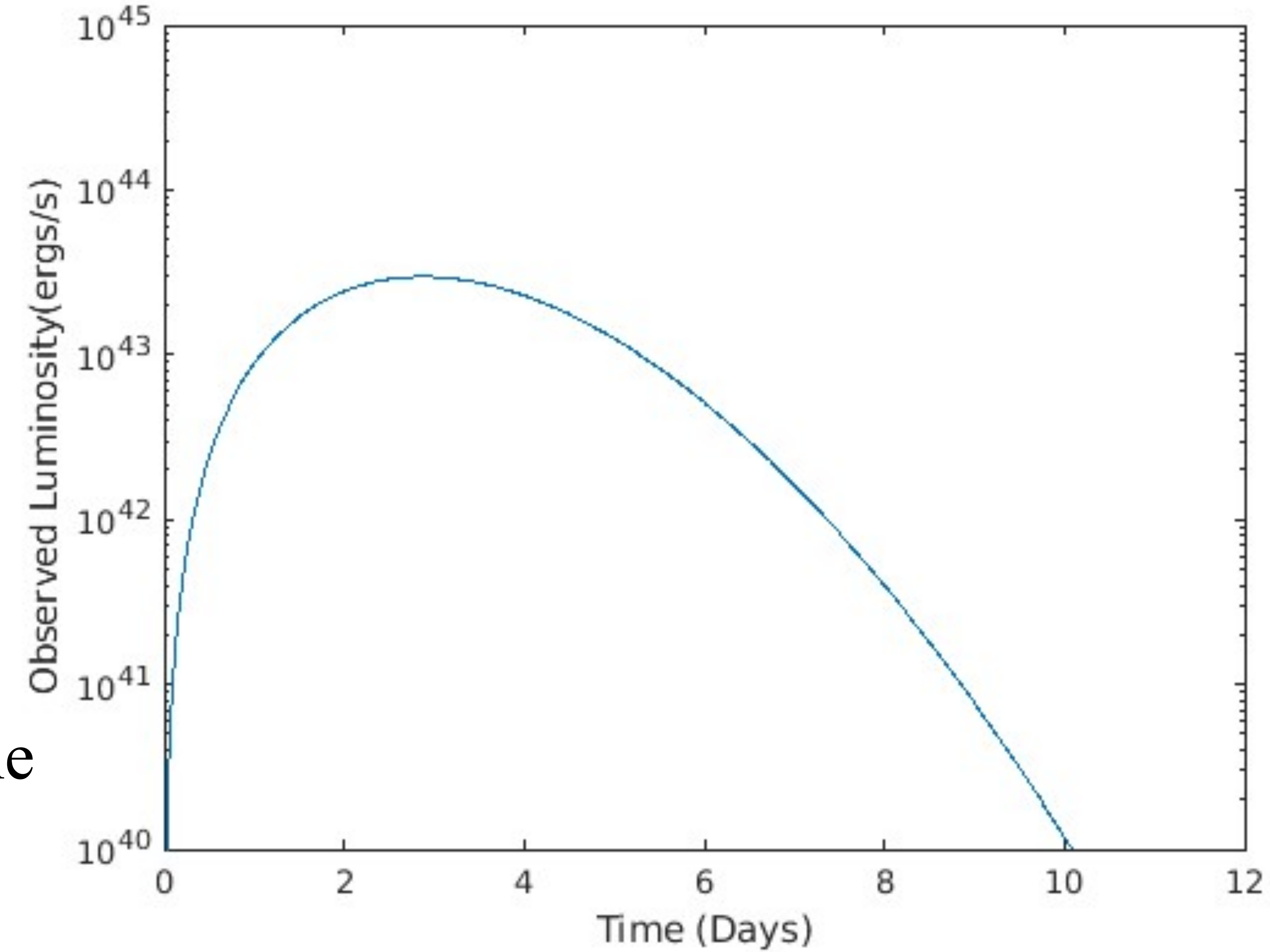
In order to reach our target horizon it will be crucial to:

1. improve existing pipelines or develop novel search methods, by means of template signal injections to check the efficiency of different schemes

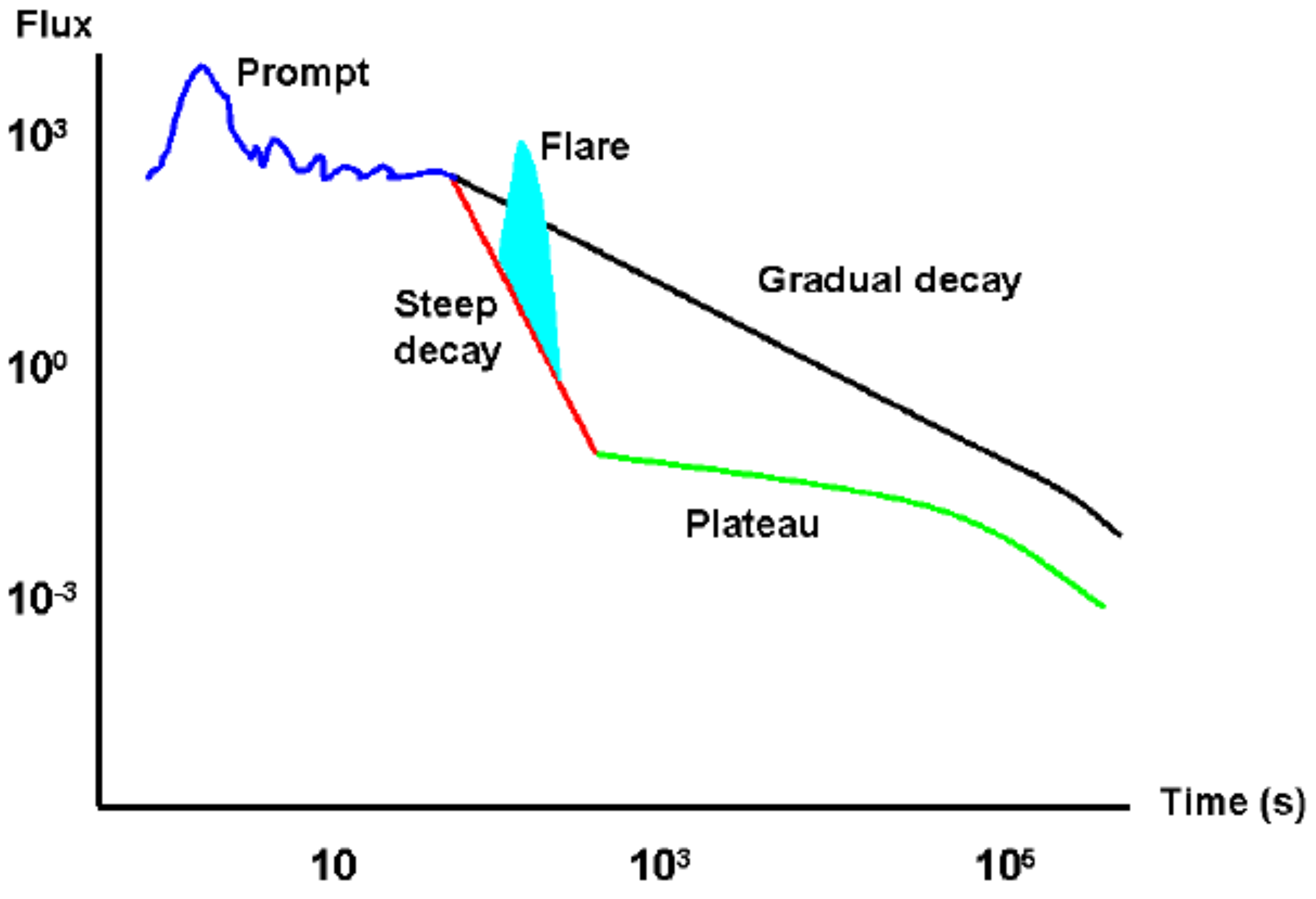
2. obtain external EM triggers, that help enhance the statistical significance of possible candidates and help the search efficiency by restricting the parameter space

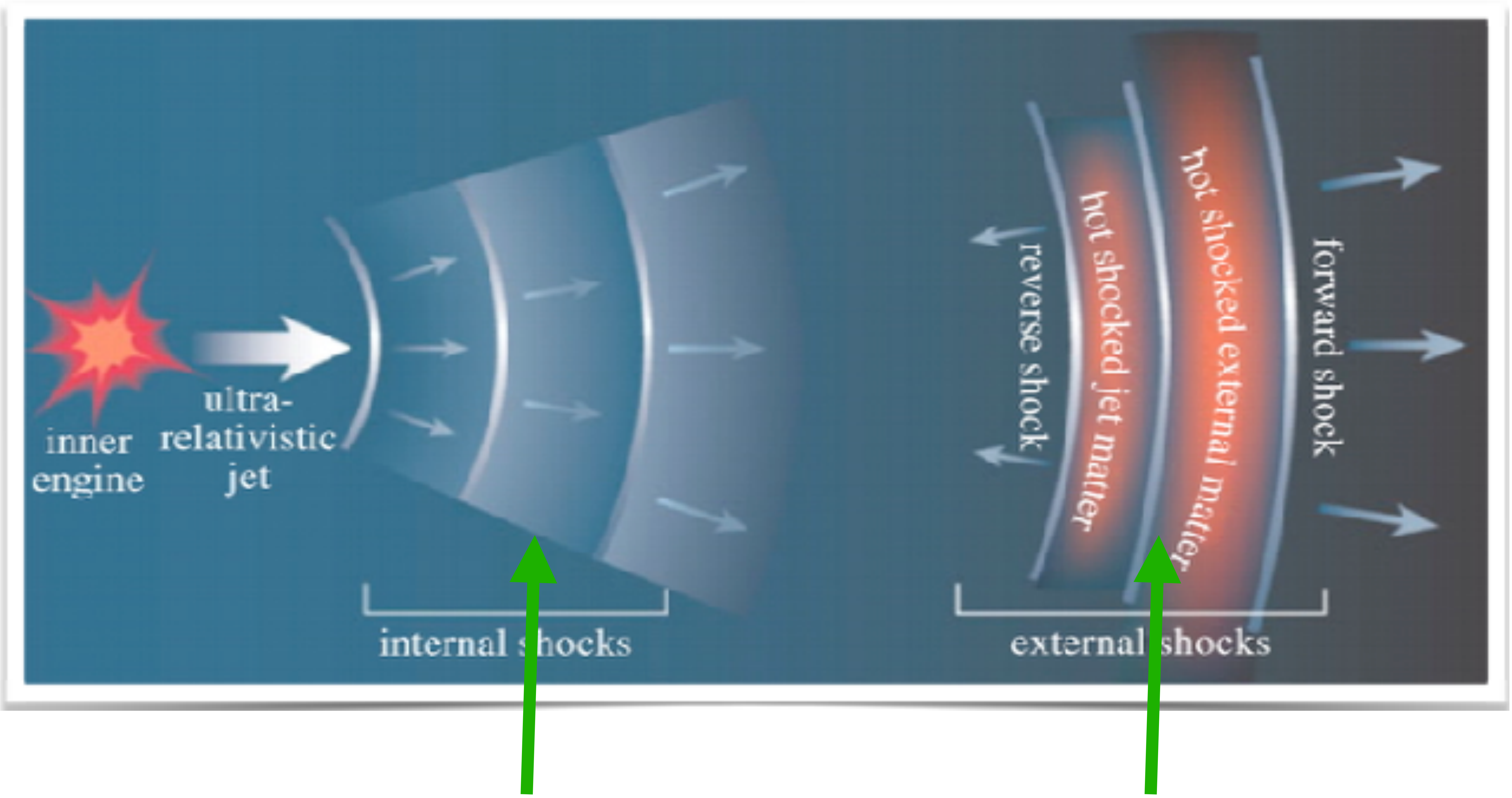


Example of UV/optical shock break-out light curve expected after a magnetar's birth.
Systematic study under way in view of the launch of the dedicated UV Israel-US satellite Ultrasat (2025)

ASTROPHYSICAL IMPLICATIONS (A)

Gamma-Ray Bursts (GRBs)





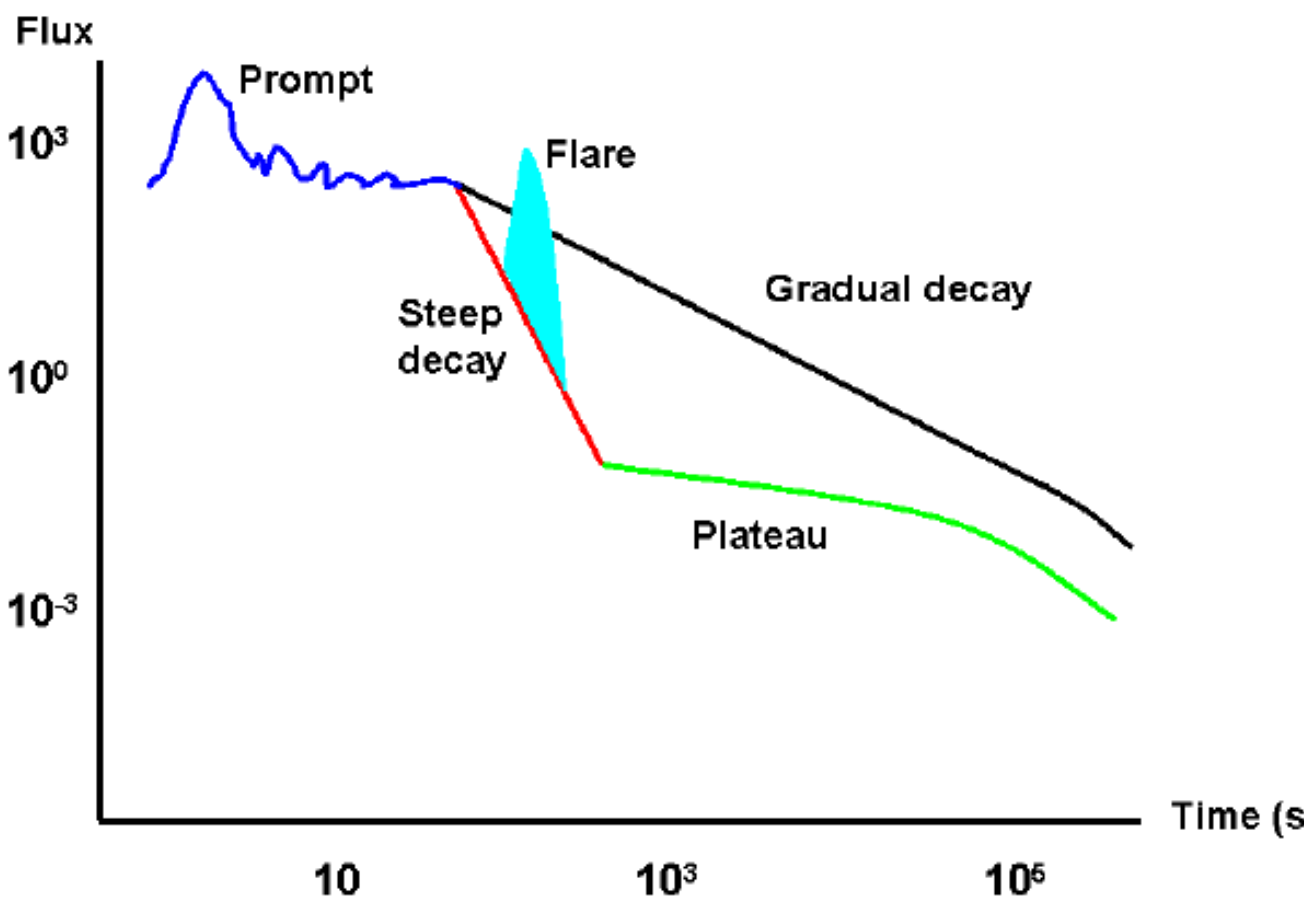
Prompt phase (~ seconds)

Afterglow emission (~hours/days)

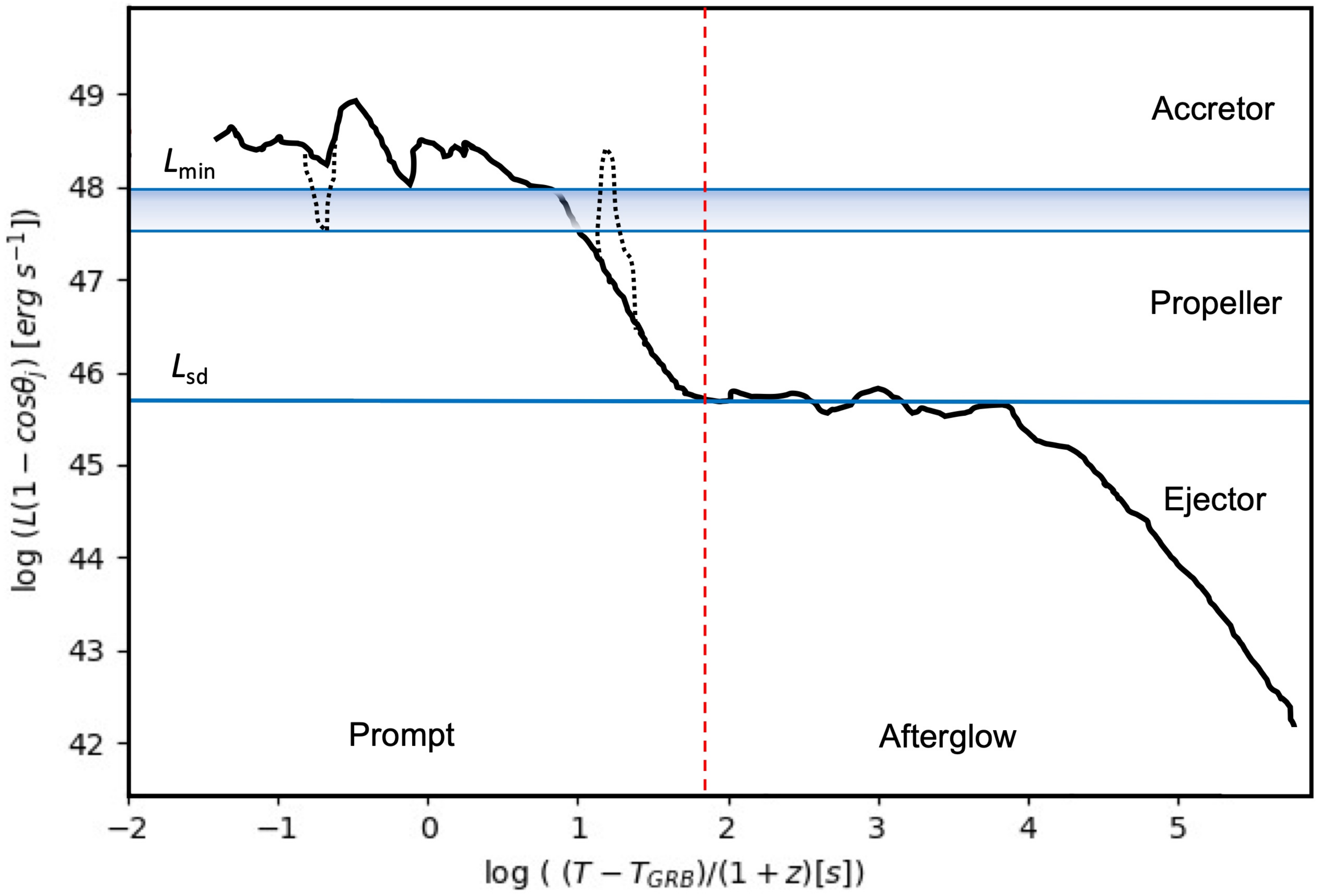
ASTROPHYSICAL IMPLICATIONS (A)

Dall'Osso et al. 2023 (submitted)

Gamma-Ray Bursts (GRBs)



NS central engine: accretion+spindown energy



$$L_{\rm min} = 1.4 \times 10^{37} \text{ erg s}^{-1} \, \epsilon_r \left(\frac{\mu}{10^{30}}\right)^2 P^{7/3} \left(\frac{\xi}{0.5}\right)^{7/2} R_{\rm 10Km} \, M_{1.4}^{-2/3}$$

ASTROPHYSICAL IMPLICATIONS (A)

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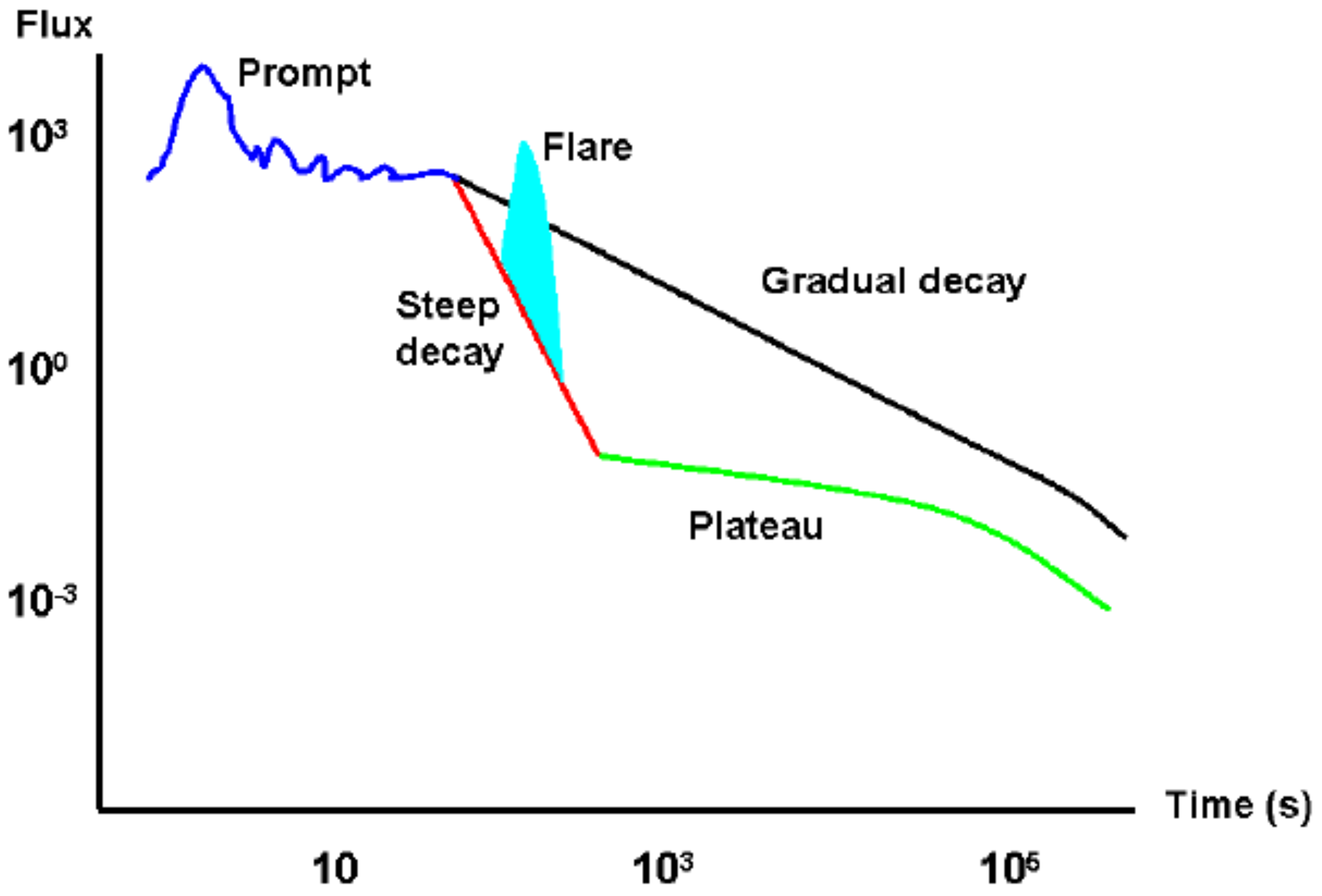
Gamma-Ray Bursts (GRBs)



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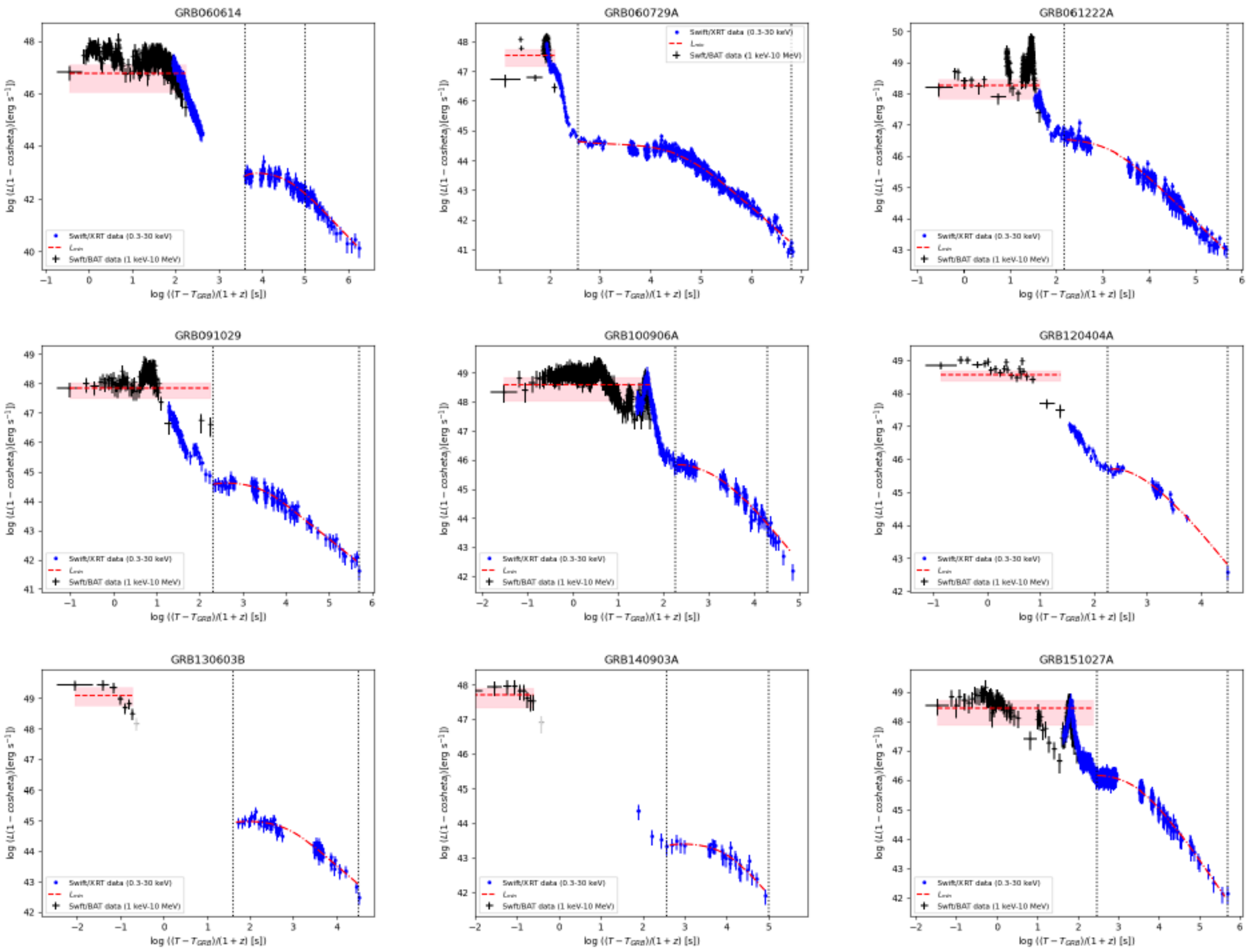
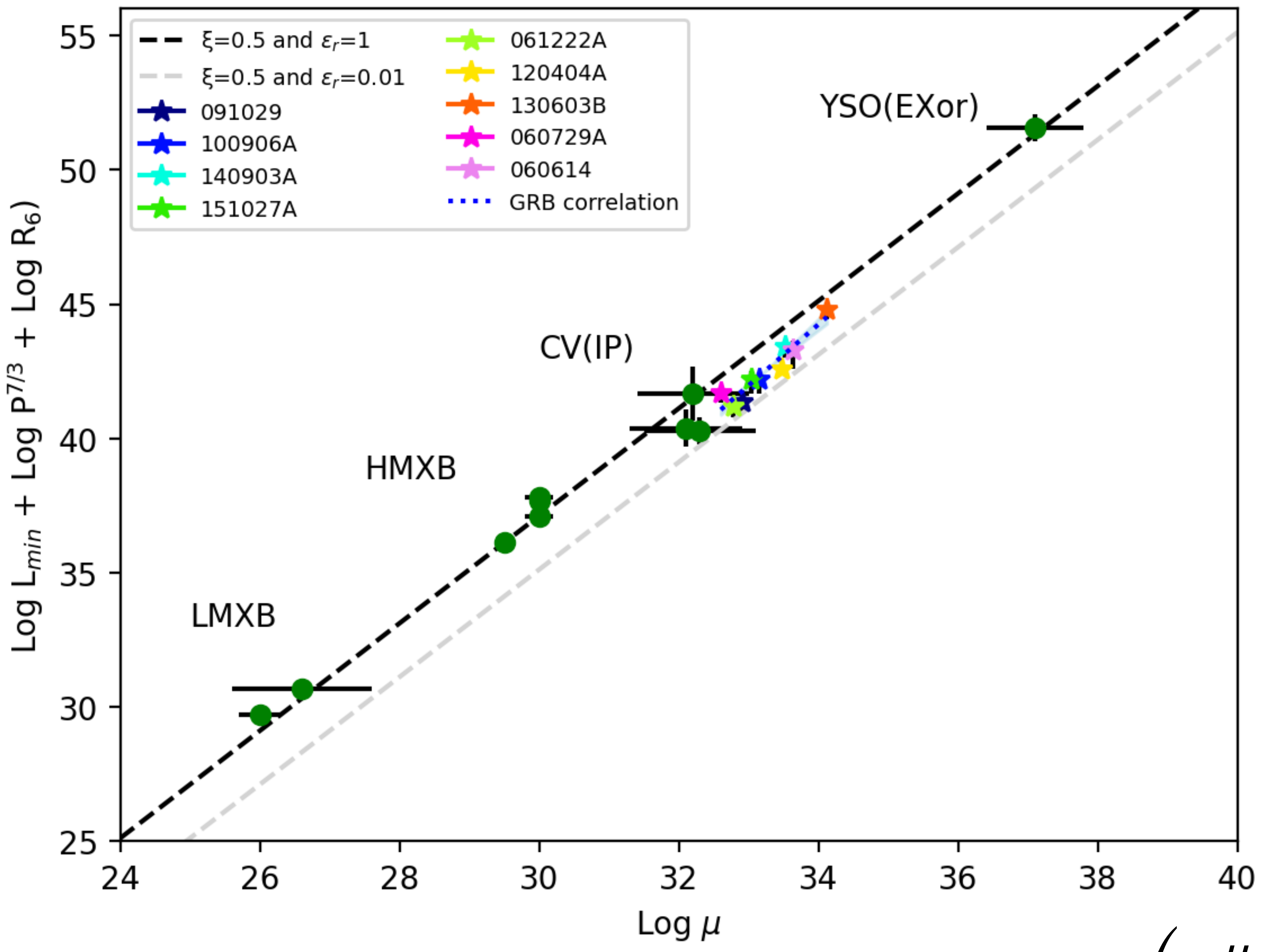
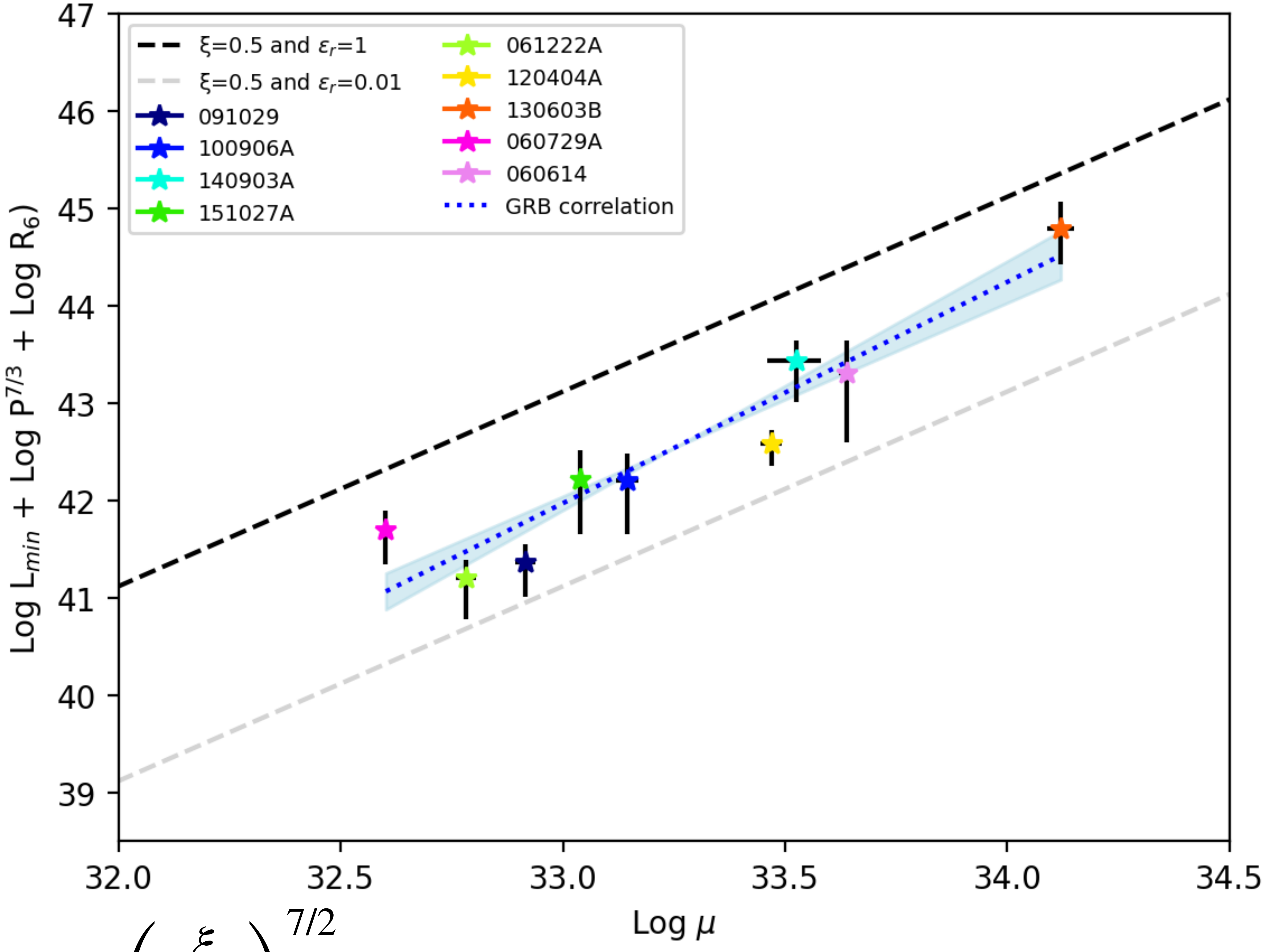


ASTROPHYSICAL IMPLICATIONS (A)

Dall'Osso et al. 2023 (submitted)

GRBs vs. Accretion-powered stellar-mass X-ray sources





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ASTROPHYSICAL IMPLICATIONS (B)

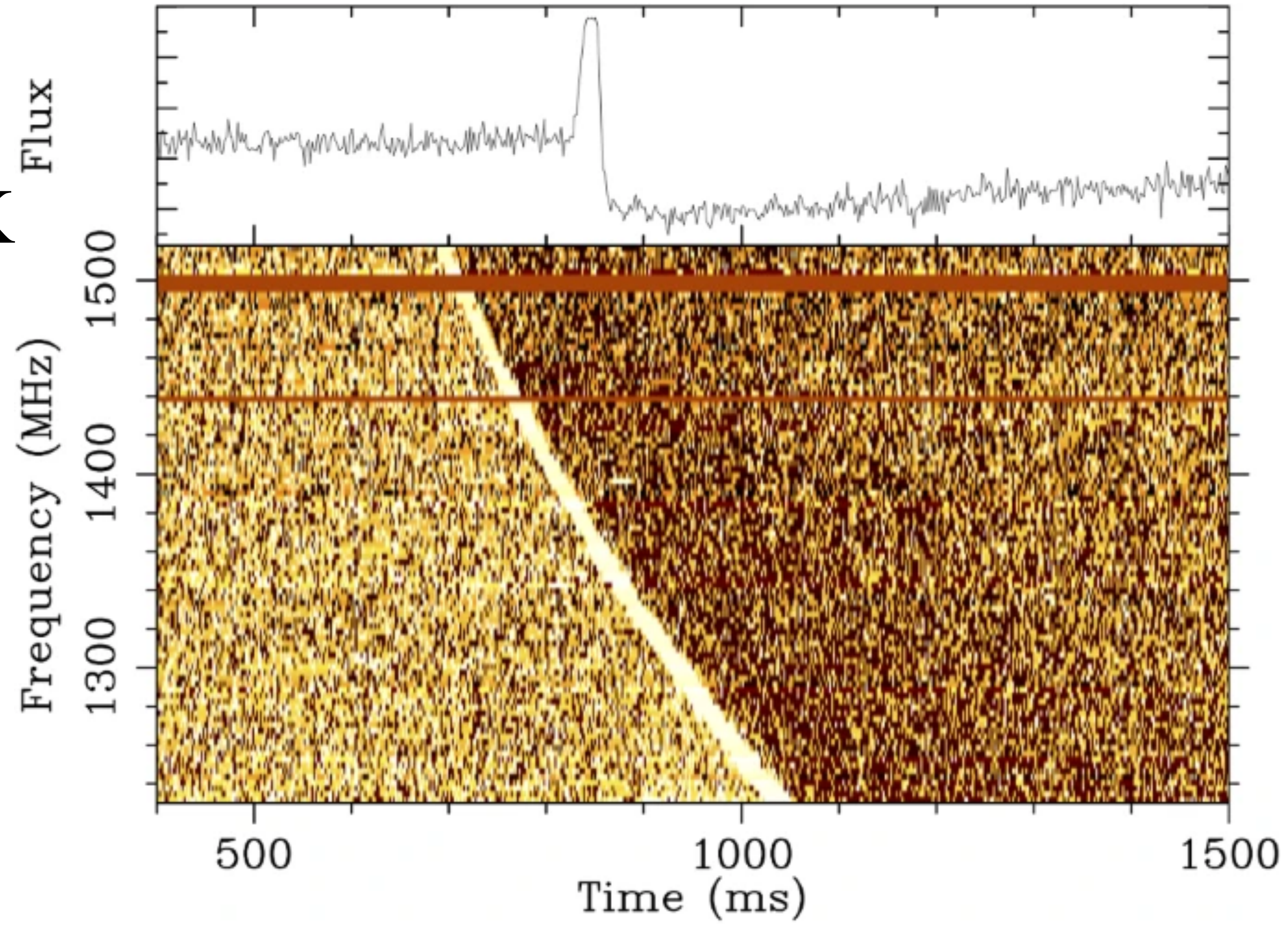
Fast Radio Bursts (FRBs)

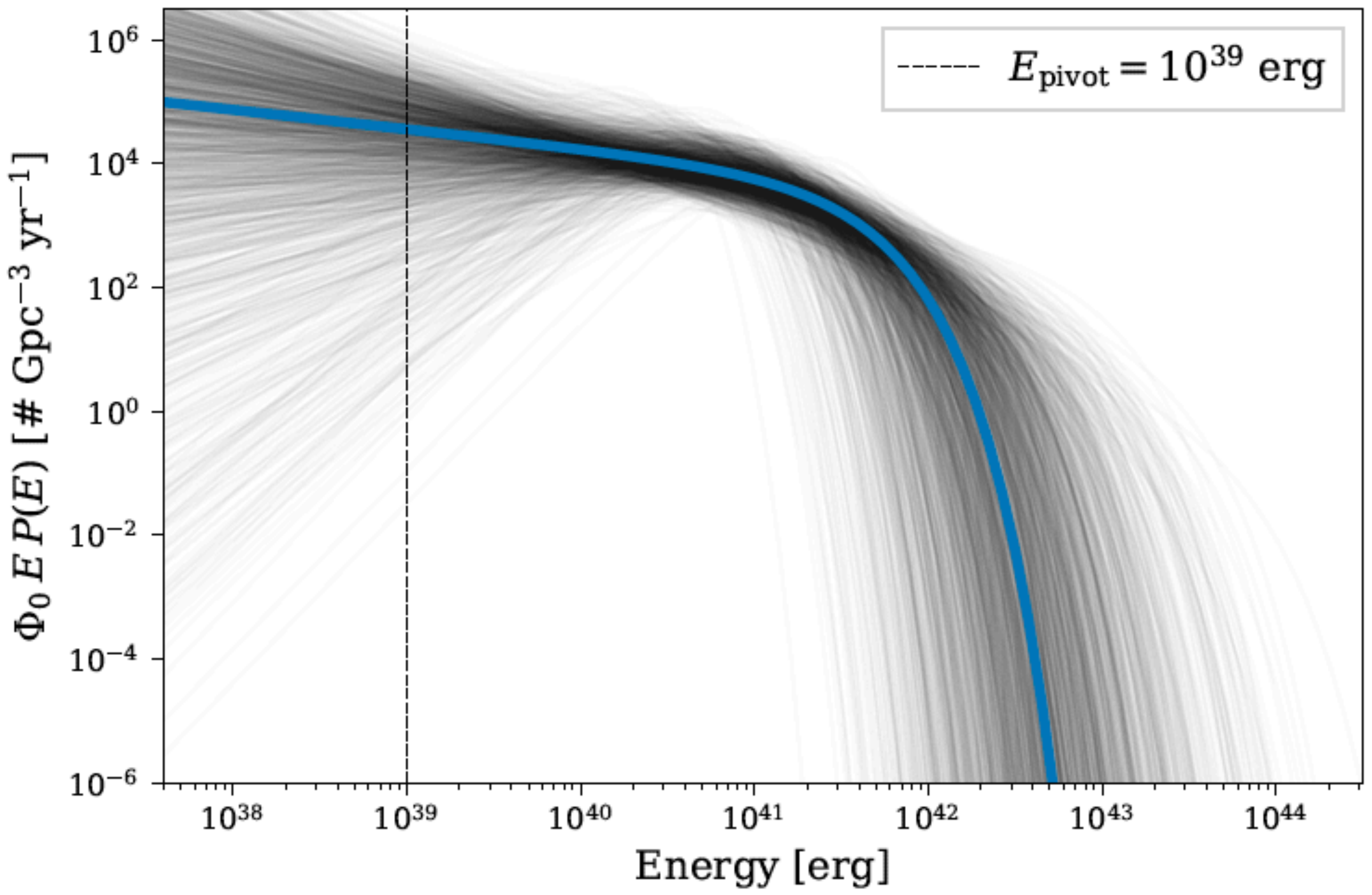
(a) ms-long radio bursts with huge brightness temperatur $T_b > 10^{31}$ K

$\Rightarrow$ coherent emission

$$\Delta E \sim 10^{37} - 10^{42}\ \text{erg}$$

(b) some are repeating sources, a few of which have host galaxies/persistent radio counterparts $\Rightarrow$ distance, etc





$$\frac{dN}{dE} \propto E^{-\gamma}$$

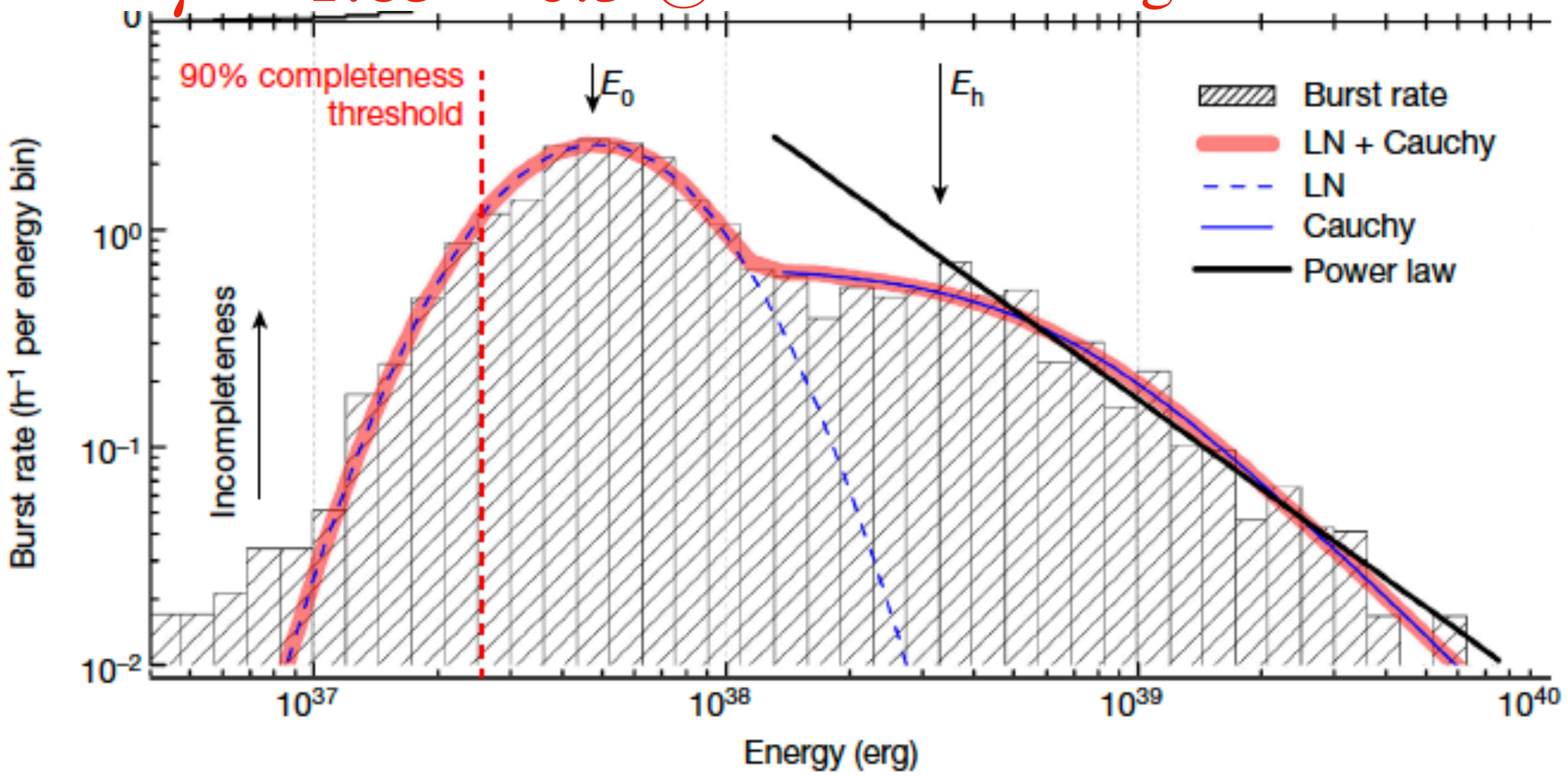
$\gamma = 1.4^{+0.7}_{-0.4}$

$\gamma = 2.1^{+0.15}_{-0.1}$

$\gamma = 1.8^{+0.3}_{-0.3}$

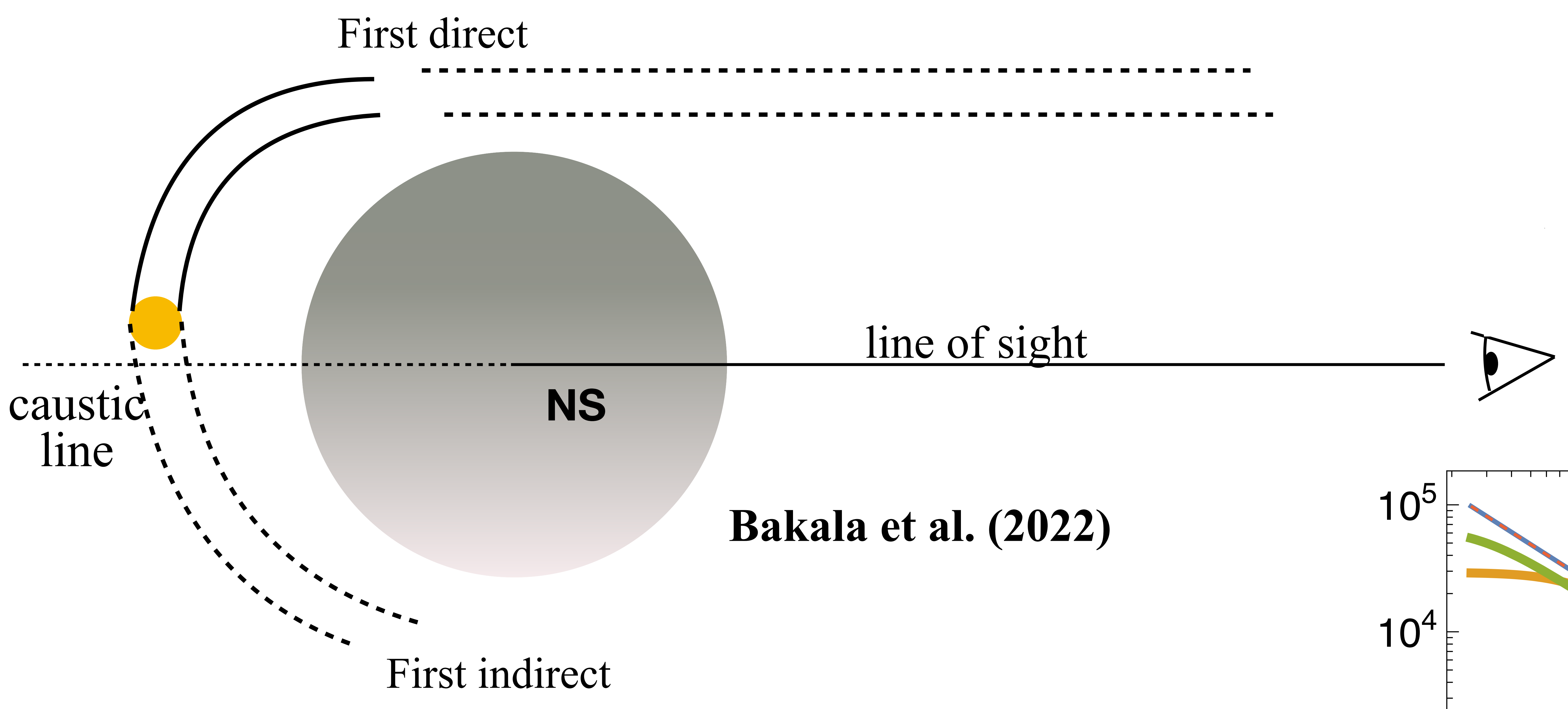
$@E > 10^{39}$ erg

$\gamma = 1.85 \pm 0.3\ @E > 4 \times 10^{38}$ erg

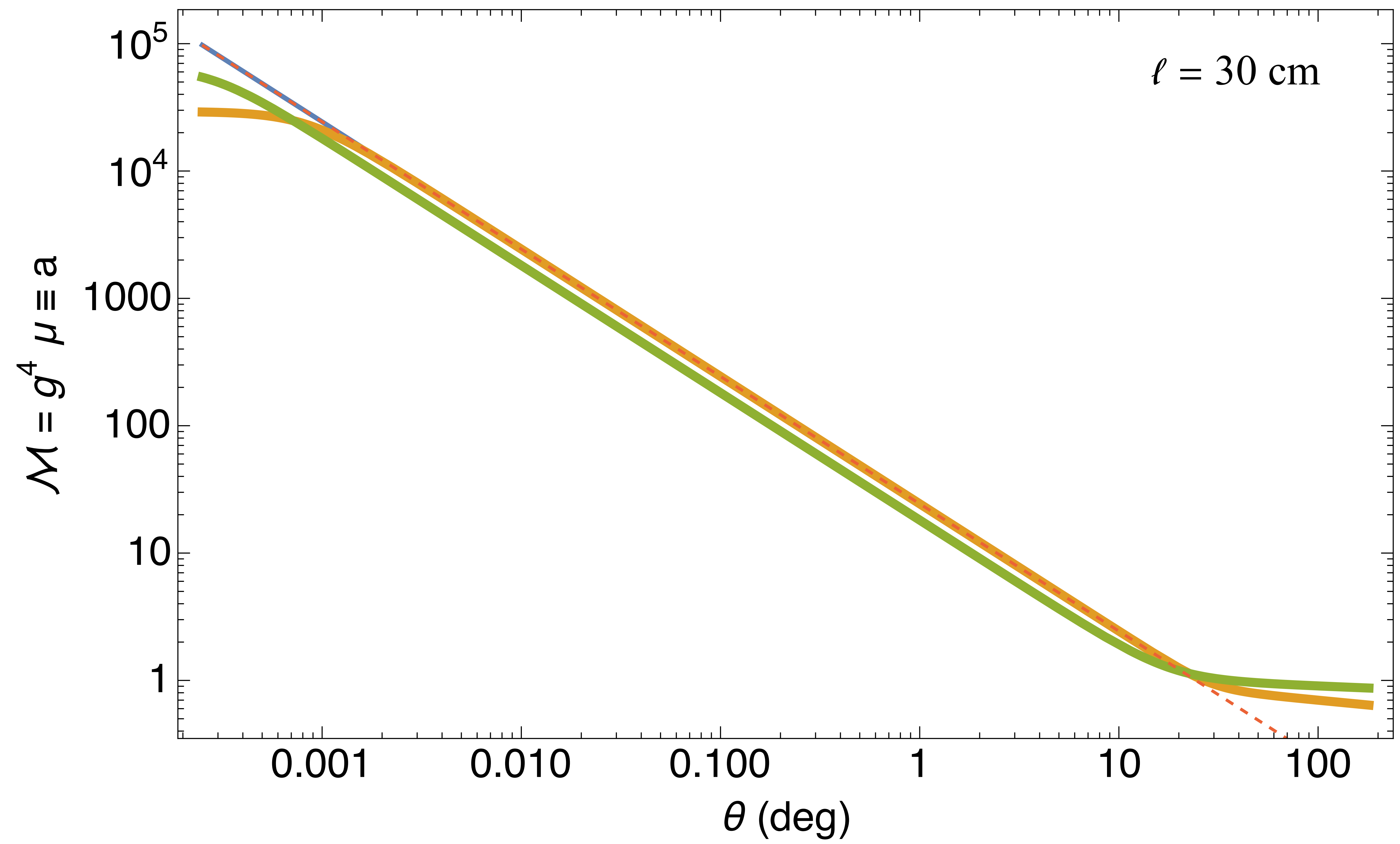


SEARCHING MORE INFO FROM EM OBSERVATIONS: FRBs

Gravitational lening in the strong field regime (extreme lensing)



Bakala et al. (2022)



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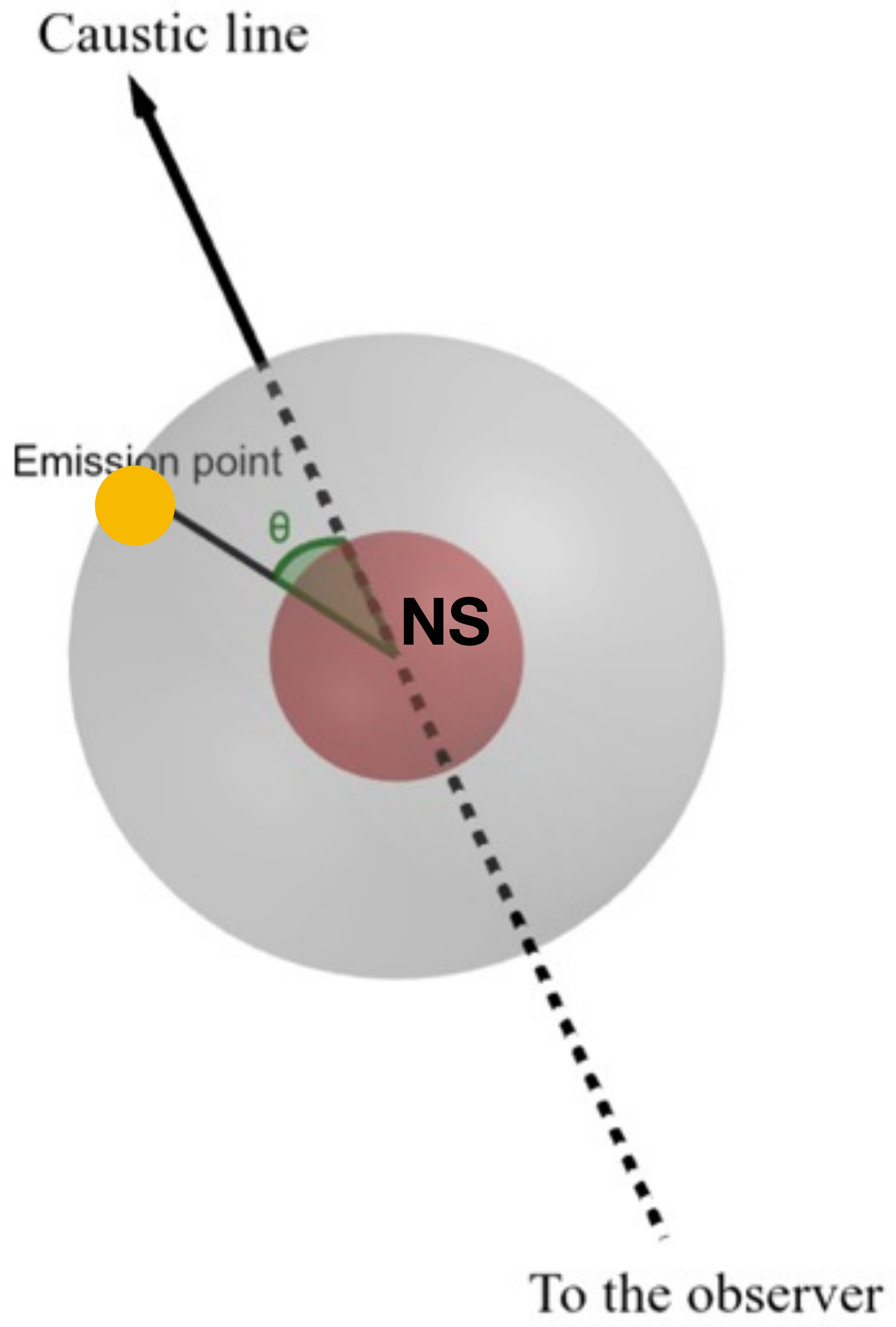
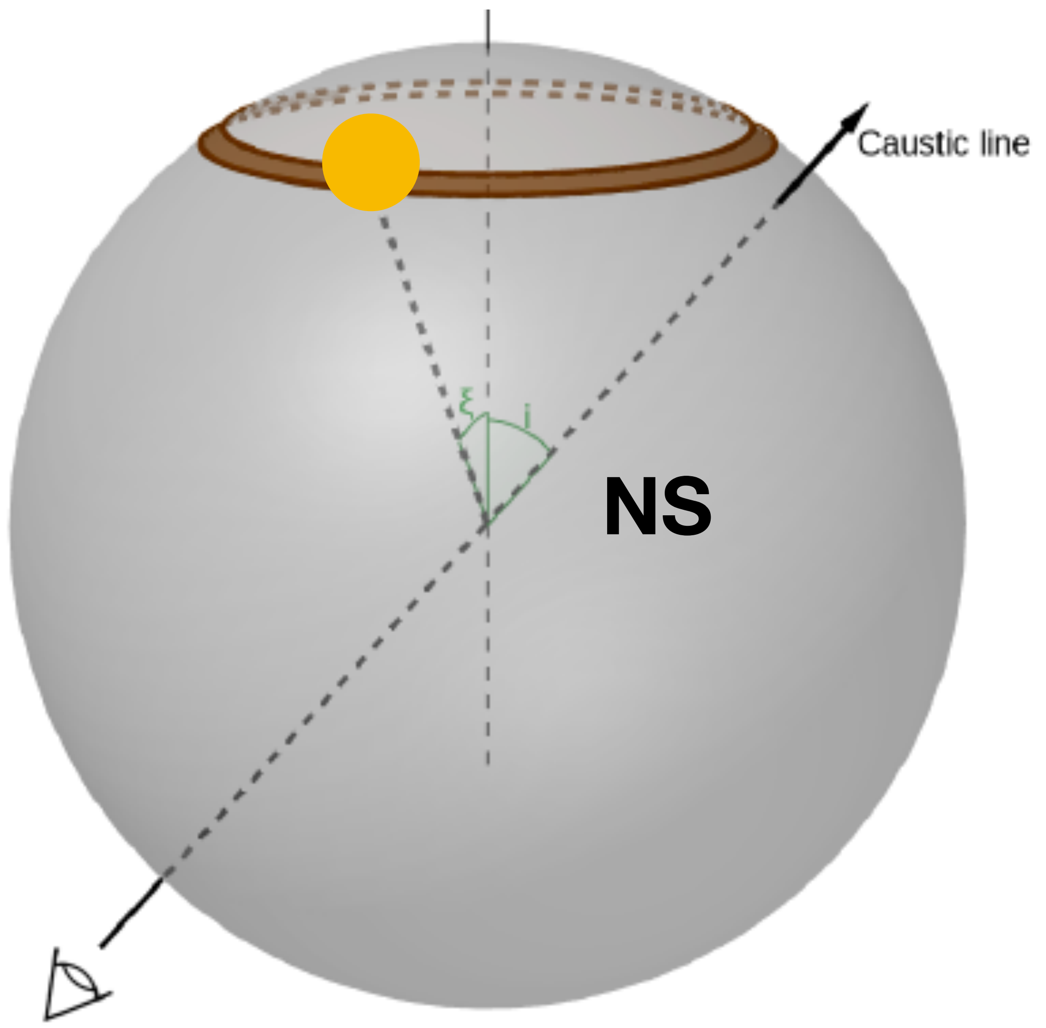
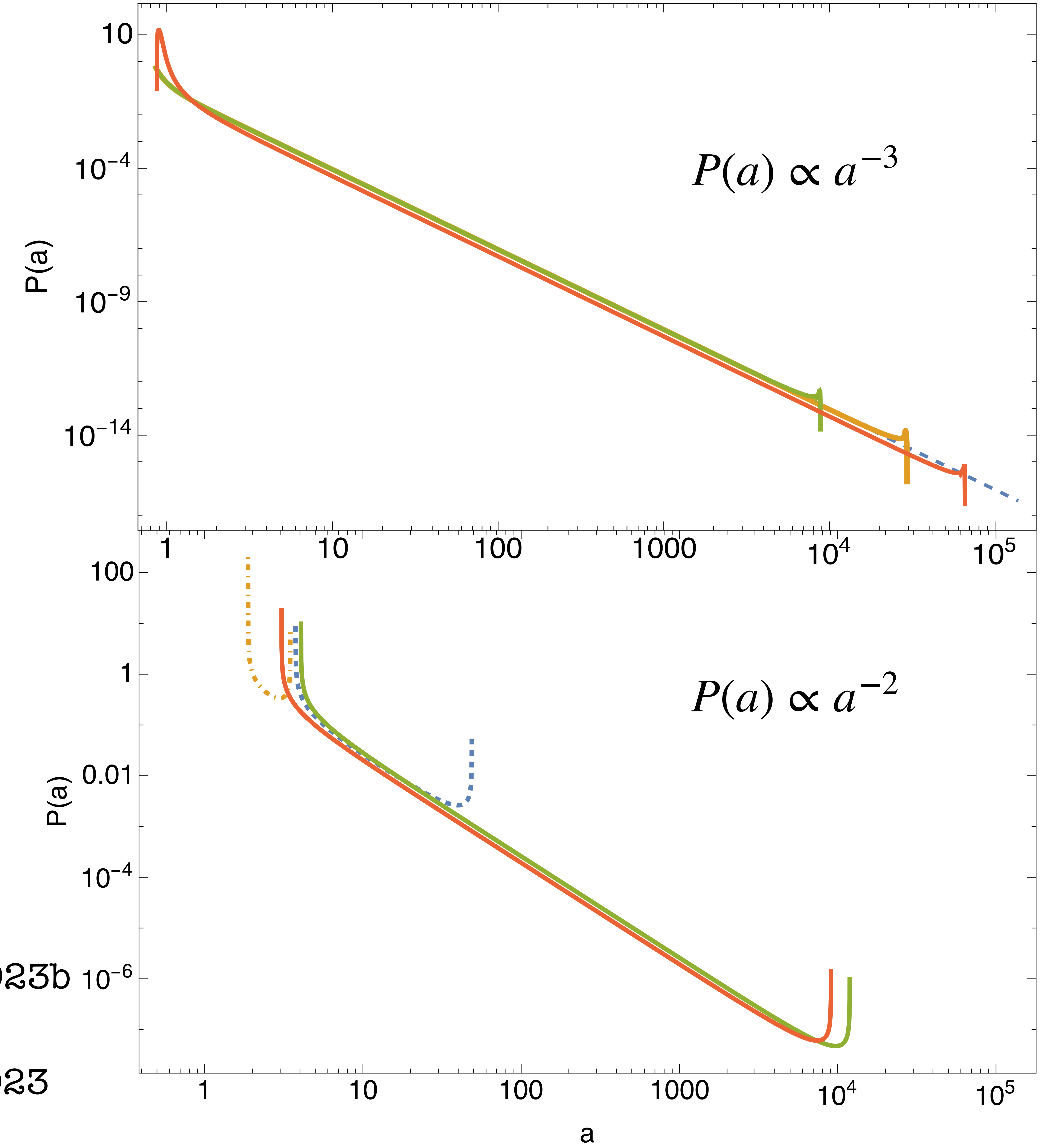




Dall’Osso, LaPlaca et al. 2023b (submitted)

LaPlaca, Dall’Osso et al. 2023 (under way)



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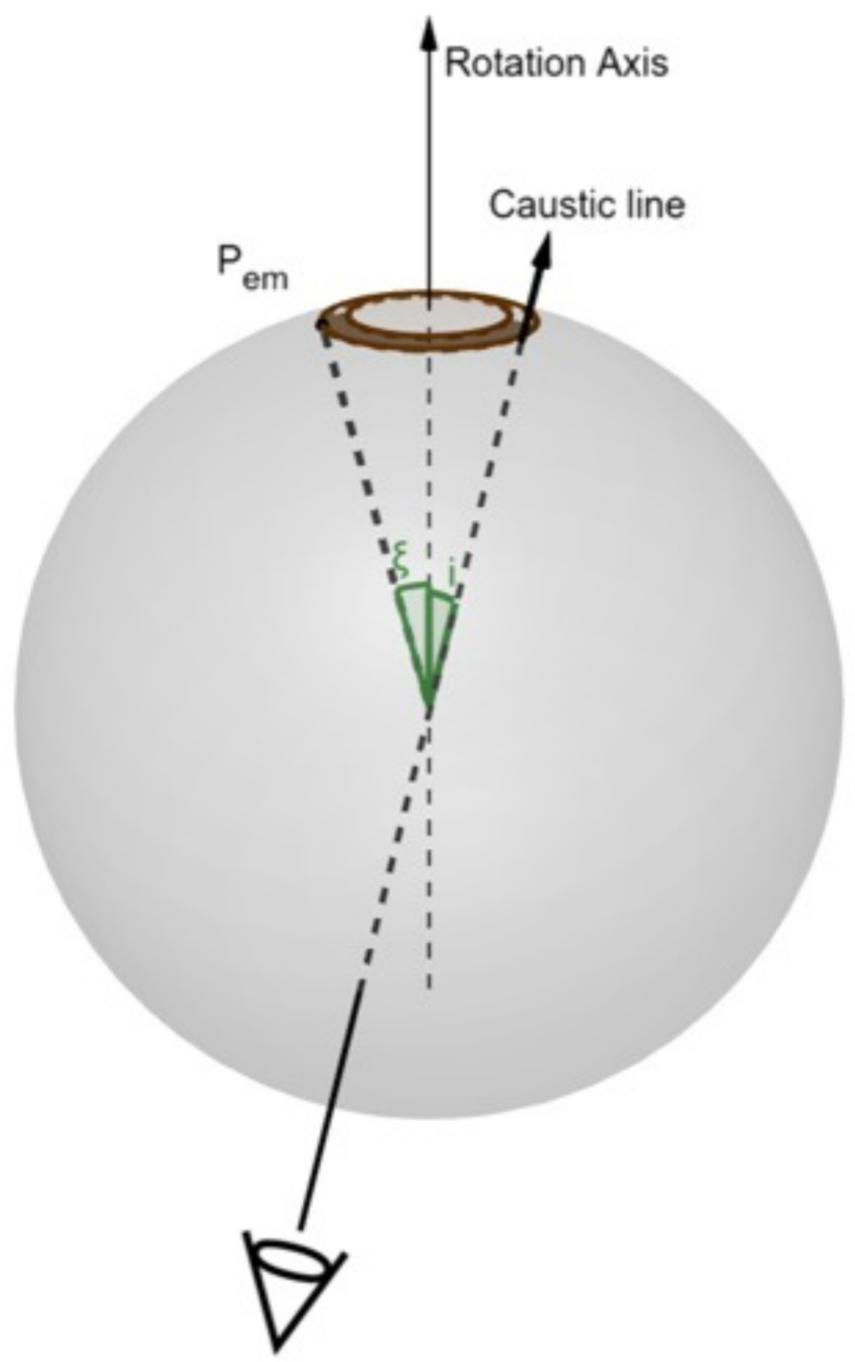
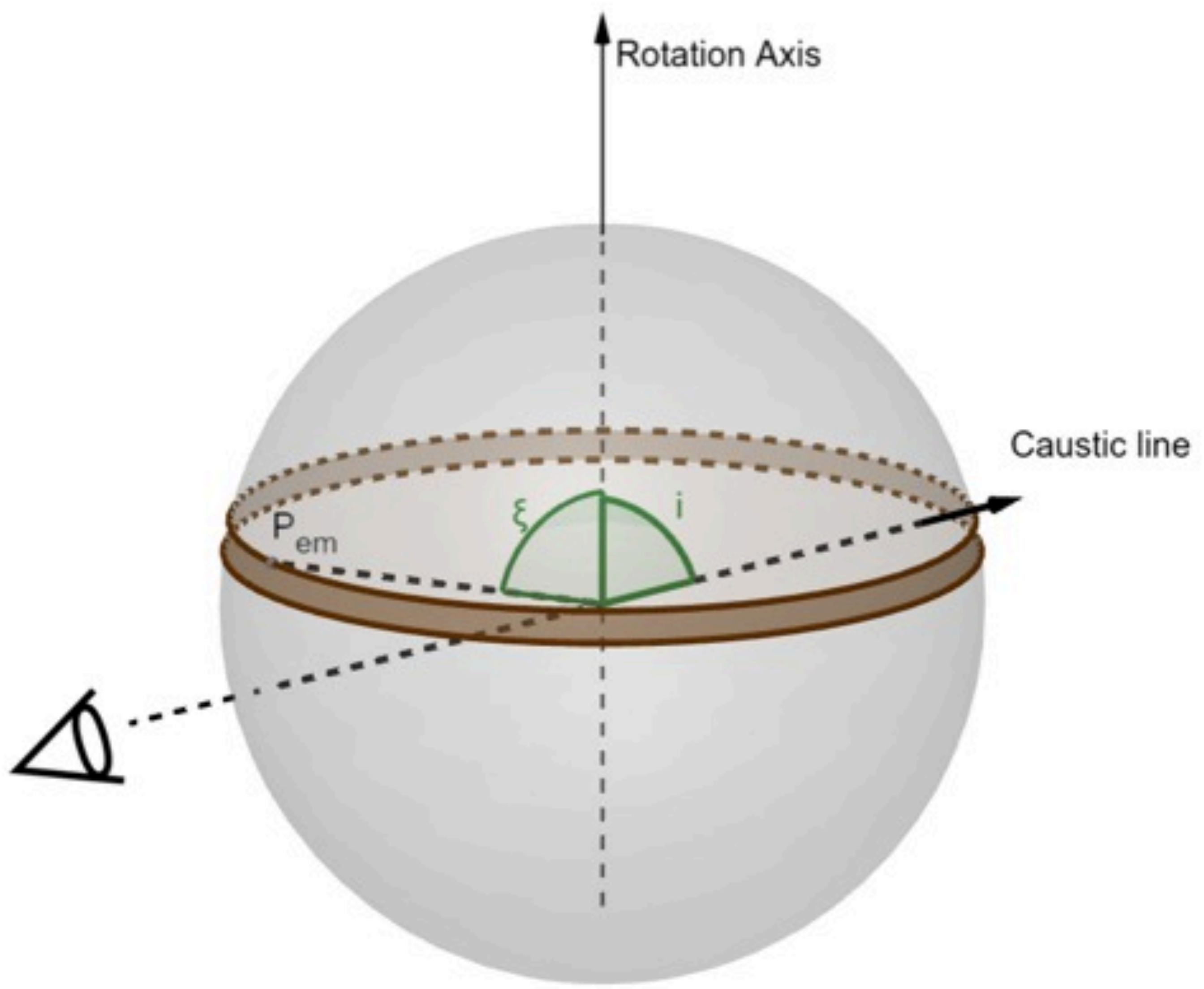
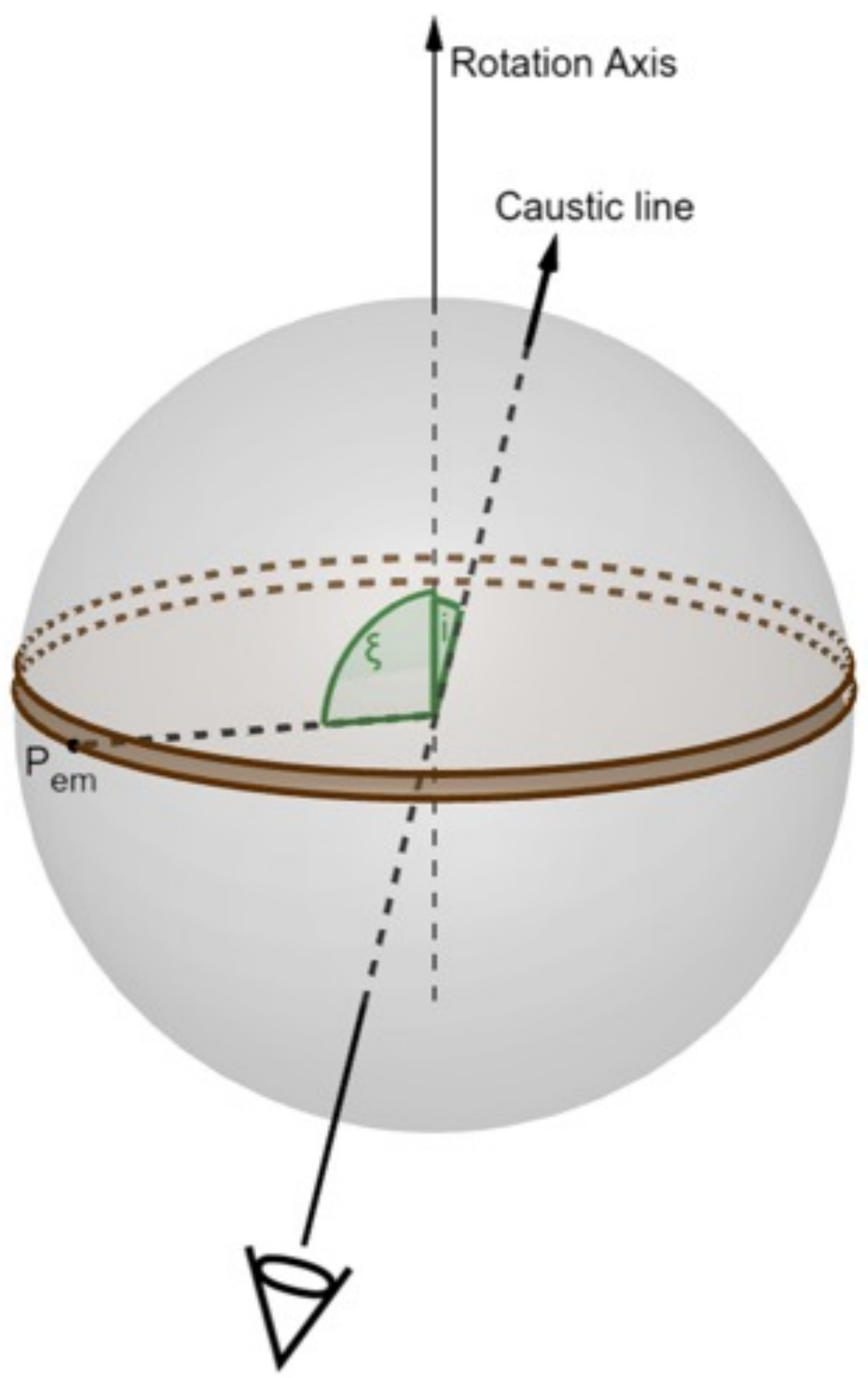


VERY FREQUENT AMPLIFICATION: repeater even with short obs. time



RARE AMPLIFICATION: one-offs (In the future, will become a repeater)

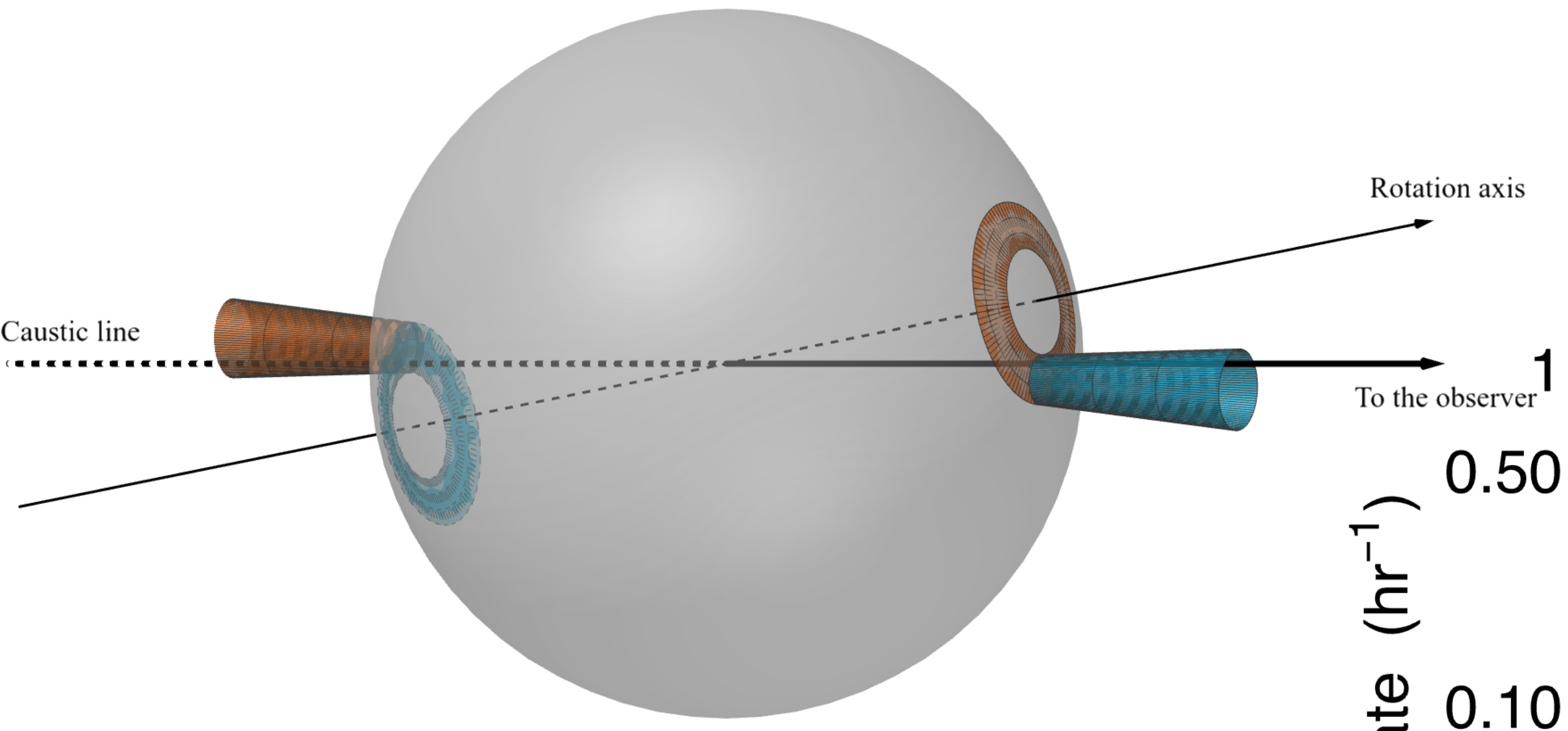


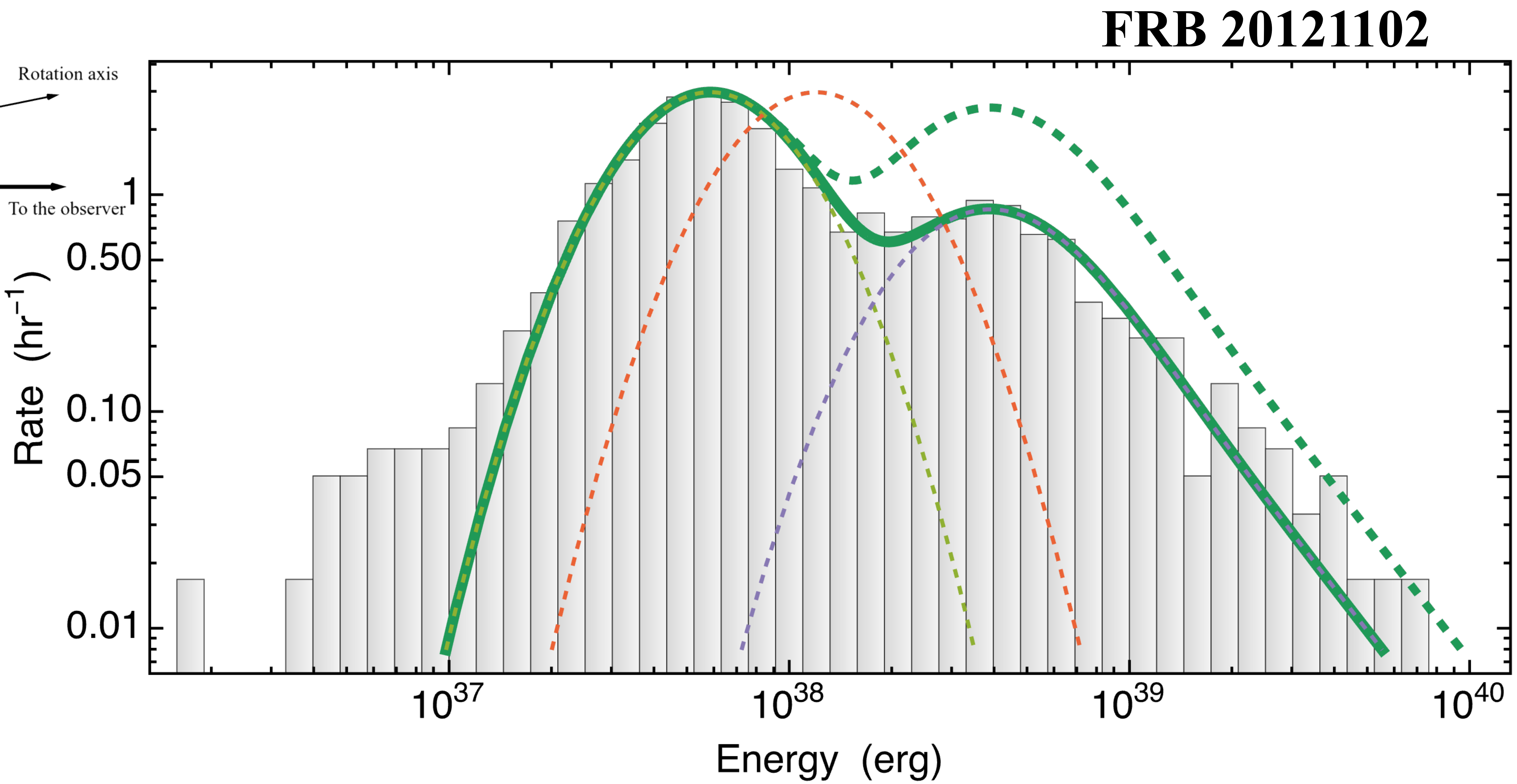
NO AMPLIFICATION: undetected (unless very nearby)

Dall'Osso, LaPlaca et al. 2023b (submitted)

LaPlaca, Dall'Osso et al. 2023 (under way)

SEARCHING MORE INFO FROM EM OBSERVATIONS: FRBs



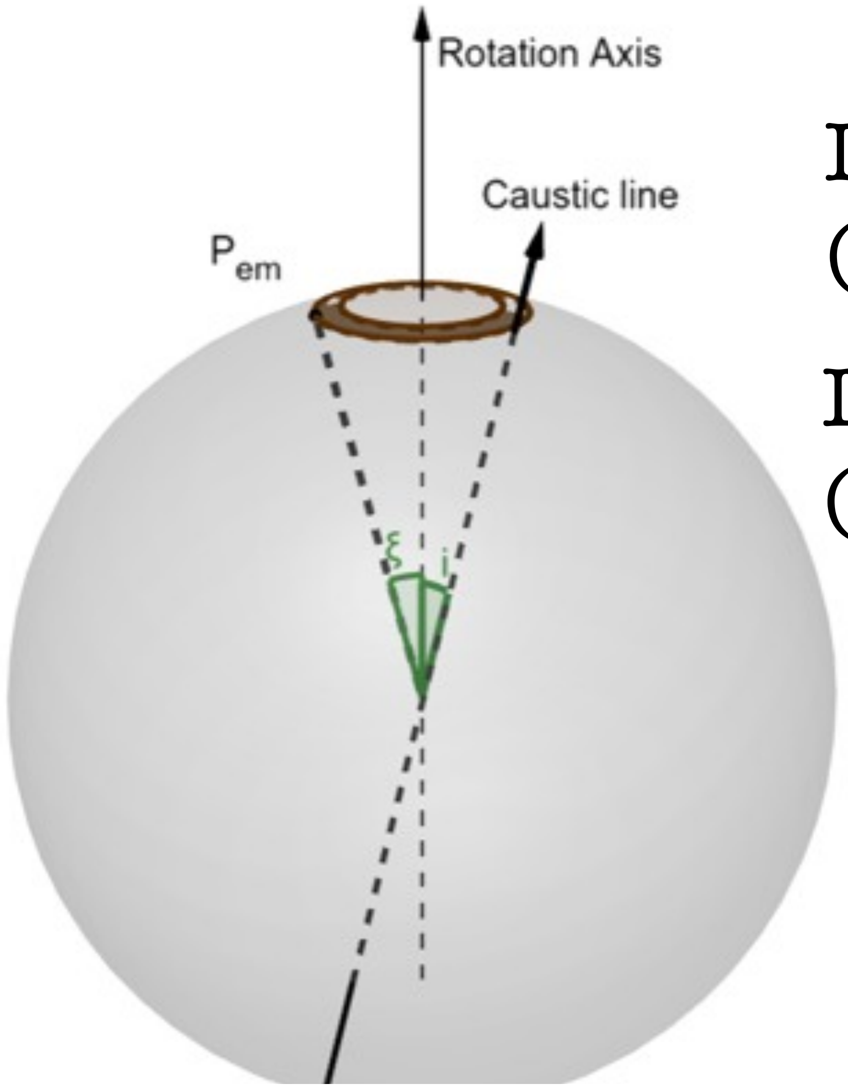


VERY FREQUENT AMPLIFICATION:
repeater even with short obs. time

Dall'Osso, LaPlaca et al. 2023b (submitted)

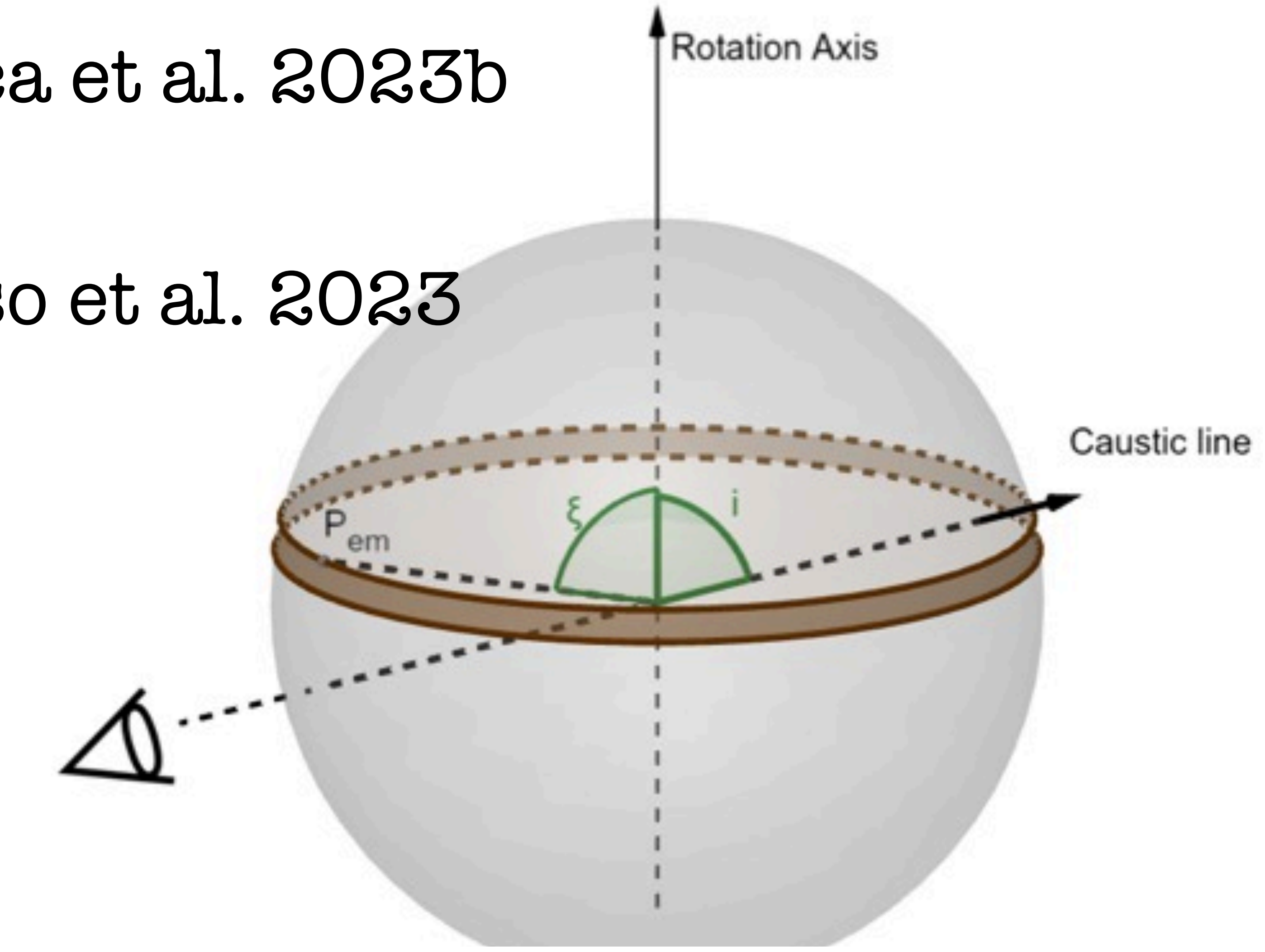
LaPlaca, Dall'Osso et al. 2023 (under way)

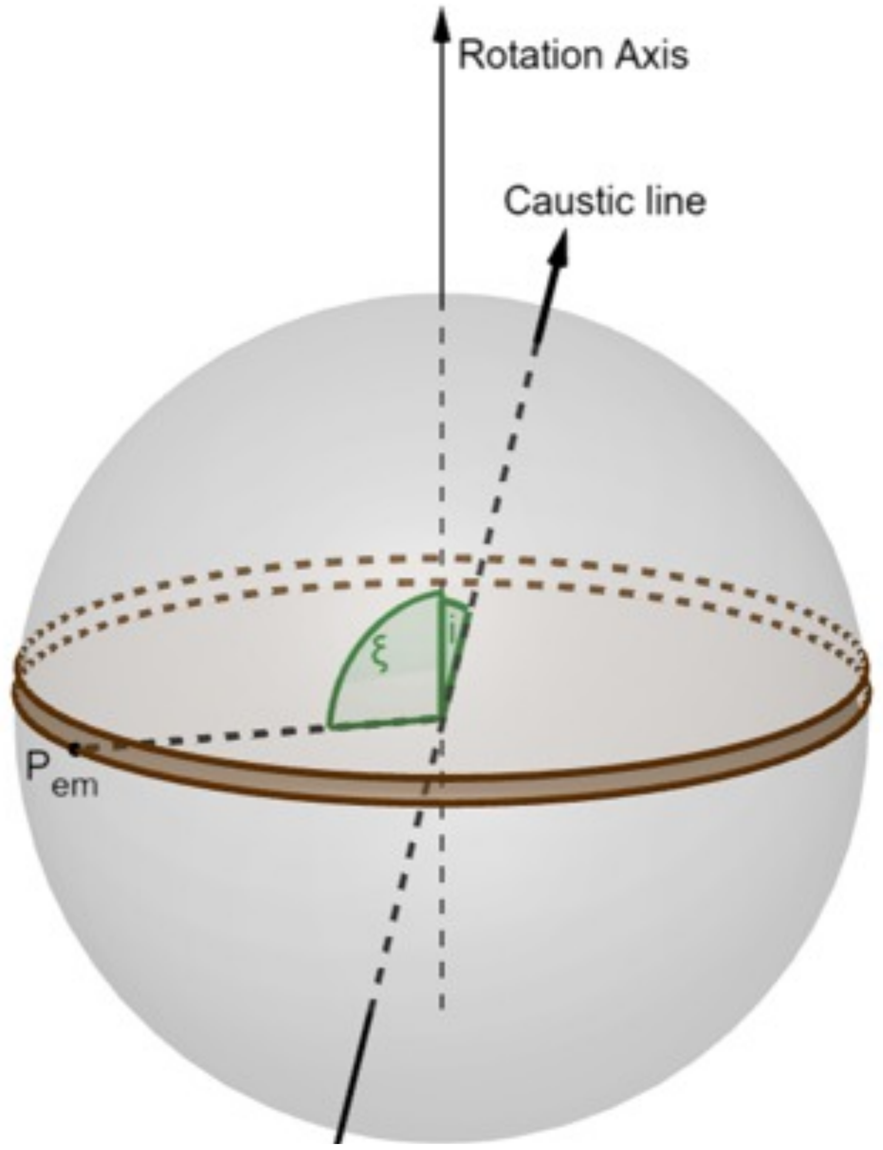
SEARCHING MORE INFO FROM EM OBSERVATIONS: FRBs

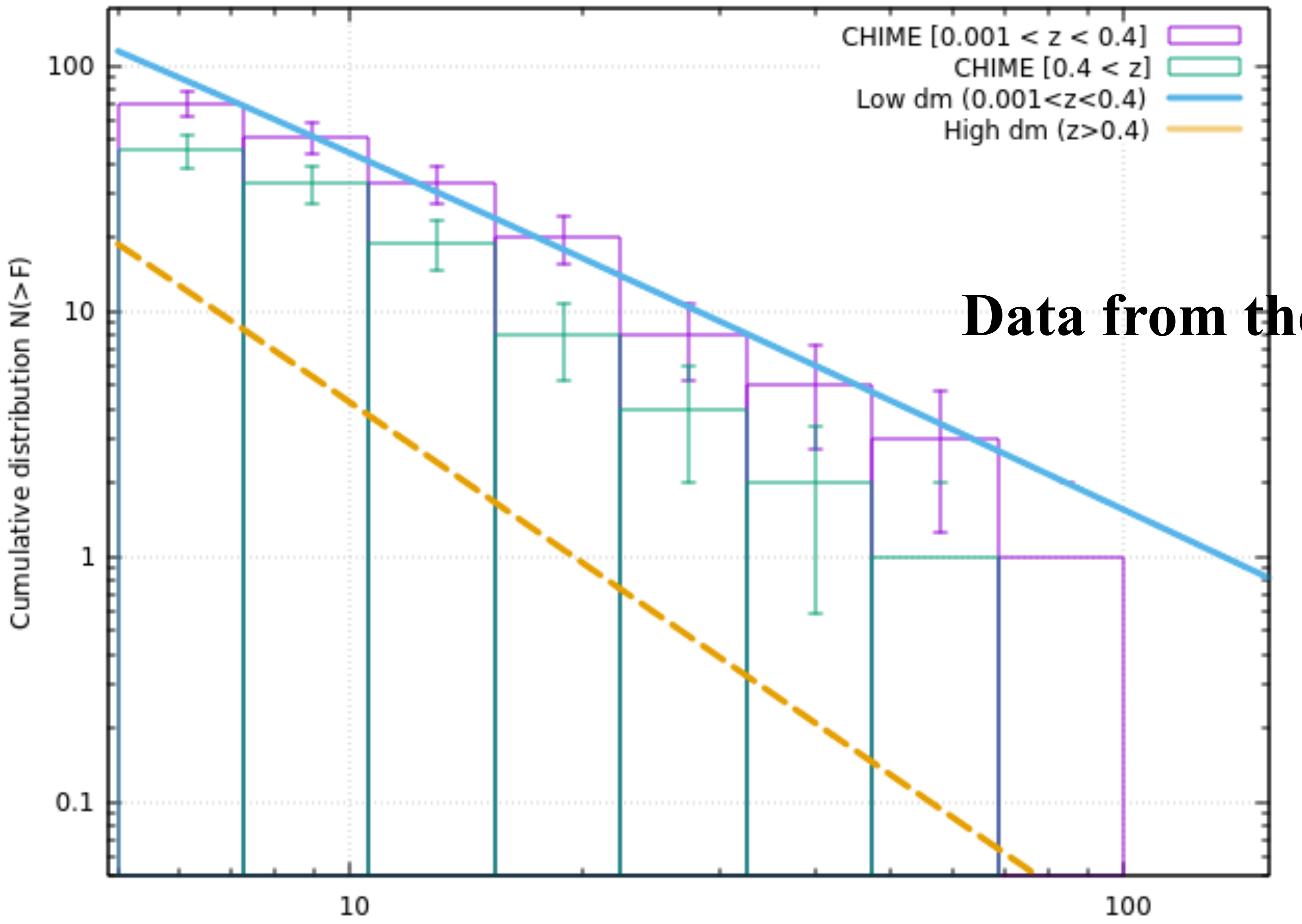


Dall'Osso, LaPlaca et al. 2023b (submitted)

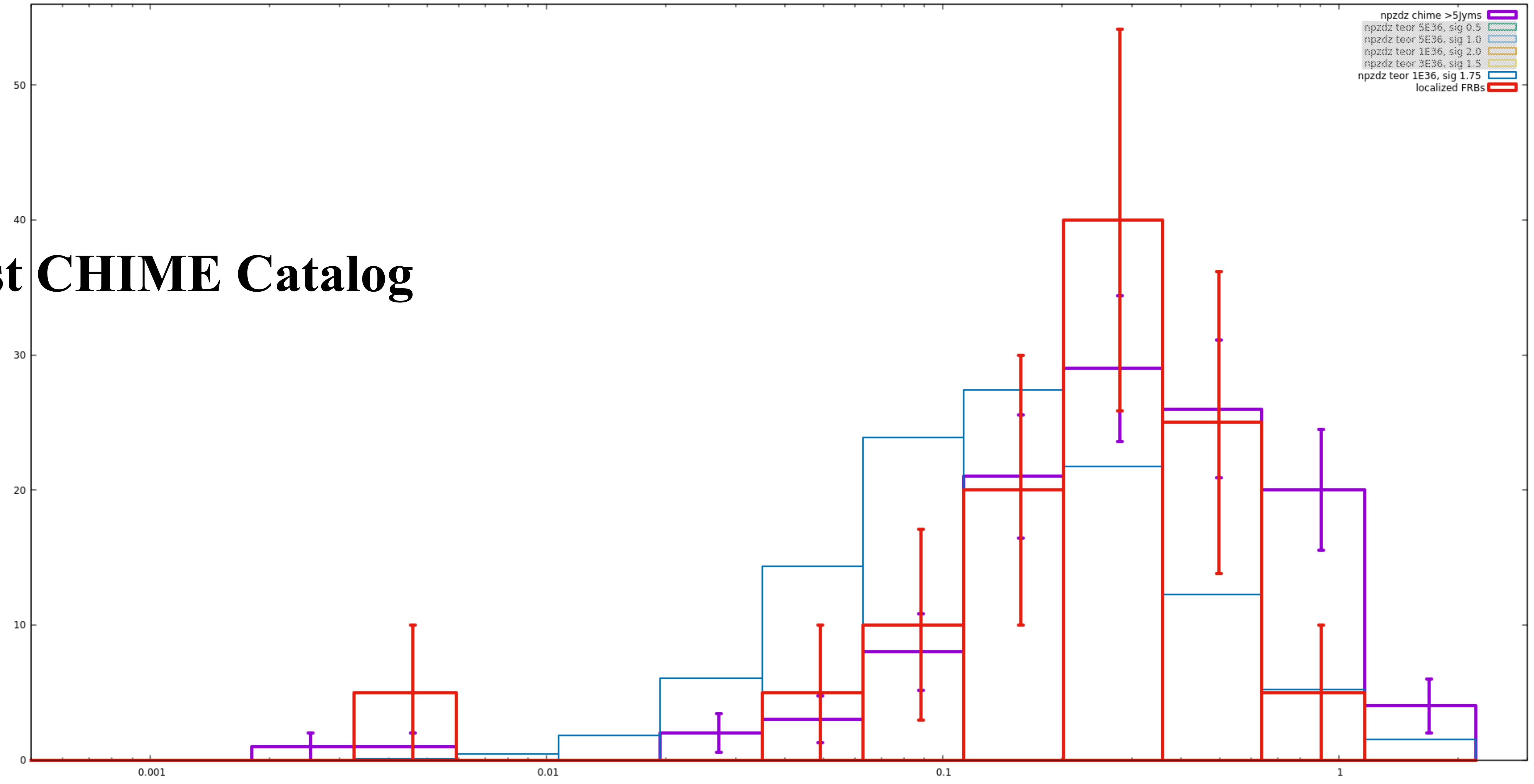
LaPlaca, Dall'Osso et al. 2023 (under way)







Data from the First CHIME Catalog



TIMELINE & OUTLOOK

1. **Further investigated and confirmed viability of millisecond NS as GRB central engines**
   Longer-term goal: modelling of GRB broadband afterglows in order to ultimately identify the nature of plateaus and of their central engines. Crucial to characterise the cosmic magnetar population and its physics parameters.

2. **(closing in)** detailed study of the FRB population (repeaters vs. non-repeaters, global energetics, energy distribution of individual events, redshift distribution of sources).
   Longer-term goal: clarifying the link between FRBs and the extragalactic population of (young) magnetars. Crucial to characterise the cosmic magnetar population and its physics parameters.

3. **(in progress)** developing an ad-hoc search pipeline, building on existing work and expertise in the Rome Group
   Longer-term goal: test search pipeline performances with different approaches (e.g. machine learning techniques, ad-hoc signal pre-processing+upgraded "standard" scheme)

4. **(in progress)** observing strategy which includes multi-band EM observations aimed at identifying the early signatures from the core-collapse of a massive star (e.g. shock break-out), or even the EM signal from a newborn magnetar, exploiting existing or forthcoming satellites (optical: Sifap 2;UV: Swift-UVOT/XRT)